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SPACE STATION SYSTEMS TECHNOLOGY STUDY

Final Report

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VOLUME II

TRADE STUDY AND TECHNOLOGY SELECTION, TECHNICAL REPORT

D180-27935-2

Conducted for NASA Marshall Space Flight Center

Under Contract Number NAS8-34893

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Boeing Aerospace Company

Spectra Research Systems

FOREWORD

The Space Station Systems Technology Study (Contract NAS8-34893) was initiated in June 1983 and to be completed in April 1984. The study was conducted for the National Aeronautics and Space Administration, Marshall Space Flight Center, by the Boeing Aerospace Company with Spectra Research Systems as a subcontractor. The study final report is documented in three volumes.

D180-27935-1	Vol. I	Executive Summary
D180-27935-2	Vol. II	Trade Study and Technology Selection Technical Report
D180-27935-3	Vol. III	Technology Advancement Program Plan

Mr. Robert F. Nixon was the Contracting Officer's Representative and Study Technical Manager for the Marshall Space Flight Center. Dr. Richard L. Olson was the Boeing study manager with Mr. Paul Meyer as the technical leader, and Mr. Rodney Bradford managed the Spectra Research Systems effort. A listing of the key study team members follows.

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LIST OF ACRONYMS AND ABBREVIATIONS

ARPANET	Advanced Research Projects Agency Network
APSTS	Advanced Platform System Technology Study
BAC	Boeing Aerospace Company
BIT	Built in test
BTU	British thermal units
CADMS	Communications and data management station
CAE	Computer aided engineering
CAMPS	Construction and material processing station
CCD	Charge coupled device
CELSS	Controlled ecological life support system
Cg	Center of gravity
CMG	Control moment gyro
CO_2	Carbon dioxide
CPU	Central processor unit
CRT	Cathod ray tube
dc/ac	Direct current/alternating current
deg/sec	Degrees per second
DMS	Data management system
EASY	Engineering Analysis System
EVA	Extra vehicular activity
ft	feet
GL/EP	Glass/expoxy
GR/EP	Graphite/expoxy
HR	Hour
H_2O	Water
Hz	Hertz (a measure of frequency)

IAC	Integrated analysis capability
IC	Integrated circuits
I.D.	Inside diameter
IEEE	Institute of Electrical and Electronic Engineers
INDA	Interface from NASTRAN dynamics analyzer
I/O	Input/output
IOC	Initial operational capability
JSC	Johnson Space Center
KG	Kilograms
KW	Kilowatts
LAN	Local area network
lb	Pounds
lbm	Pounds-mass
LED	Light emitting diode
LIOH	Lithium hydroxide
LISP	List processor
LOARS	Land, ocean, and atmospheric research station
MBPS	Million bits per second
MCR	Martin Company Report
MHz	Megahertz
MIL-STD	Millitary standard
MIPS	Million iterations per second
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NASTRAN	NASA Structure Analyzer
NIU	Network interface unit
n-m-sec	Newton-meter-seconds
NOS	Network operating system
ns	Nanoseconds (10-9 seconds)

O.D.	outside diameter
ORACLS	Optimum regulator and control of linear systems
OTV	orbital transfer vehicle
PIN	Positive intrinsic negative
PSI	Pounds per square inch
Psia	Pounds per square inch absolute
Psid	Pounds per square inch differential
R&D	Research and development
RCA-PRICE	Radio Corporation of America Price Modeling Program
RCS	Reaction control system
RF	Radiofrequency
RI	Name of expert system to configure VAX installations
R/T	Receiver-transmitter
SAR	Synthetic aperture radar
Sec	Second
SRS	Spectra Research Systems
TCC	Trace contamination control
TDMA	Time division multiple access
TDRSS	Tracking and data relay satellite system
VAX	Virtual address extension
VCD	Vapor compression distillation
VHSIC	Very high speed integrated circuit
VLSI	Very large scale integration

1.0 INTRODUCTION

This is volume II of the final report on the Space Station Systems Technology Study conducted for the Marshall Space Flight Center (MSFC) by the Boeing Aerospace Company (BAC) and Spectra Research Systems (SRS). The overall study objective was to identify, quantify, and justify the advancement of high-leverage technologies for application primarily to the early space station. The objective was fulfilled through a systematic approach tailored to each of the technology areas studied. This volume presents the results of the technical effort. Volume III discusses the research plans developed for each of the selected high-leverage technologies.

The current Space Station Systems Technology Study was an outgrowth of the Advanced Platform Systems Technology Study (APSTS) that was completed in April 1983 for MSFC by the Boeing/SRS team. The first APSTS proceeded from the identification of 106 technology topics to the selection of five for detailed trade studies. During the advanced platform study, the technical issues and options were evaluated through detailed trade processes. Individual consideration was given to costs and benefits for the technologies identified for advancement, and advancement plans were developed. An approach similar to this was used in the current study, with emphasis on system definition in four specific technology areas.

The four study areas addressed in the Space Station Systems Technology Study are: (1) Attitude Control, (2) Data Management, (3) Long-Life Thermal Management, and (4) Automated Housekeeping Integration. These four areas are extensions of the APSTS and were conducted to facilitate a more in-depth analysis of technology issues. While each of the study areas had high-leverage technology identification as a goal, different study approaches were required. The attitude control study utilized a specific representative

configuration and determined by simulation the applicability of a low bandwidth control system for space station use. The data management study concentrated on the characterization of the architecture into structural blocks and systems to facilitate simulation planning. The thermal study focused on characterizing a two-phase heat transport systems within the long life requirement constraints. Finally, the automated housekeeping task was structured to characterize the functions of an integrating controller for an overall management system. Each of these approaches produced useful advancements in the understanding of technology issues and development needs and are discussed in detail in the following sections. The topics of discussion include the planned approach, technical discussion, summary of results, conclusions, and recommendations.

The overall study was divided into four tasks. During task 1 the design concepts required in each of the four study areas were refined. The concepts were used to describe specific technology options upon which comparative studies were conducted. Candidate high-leverage advancement technologies were then selected from the options. The cost, benefits, schedules, and life cycle costs for each of the options were evaluated in task 2. Selection of the technology advancement items was made during this latter task. Technology advancement plans were prepared for each of the selected items in task 3. All study documentation was prepared in task 4. The overall study schedule is shown in figure 1.0-1.

Seven potential technology advancement items were identified during this study. These items were analyzed and evaluated in Task 2, considering technical as well as cost benefits and schedule criteria. Study plans were prepared for each of the selected high-leverage items. These selected items are:

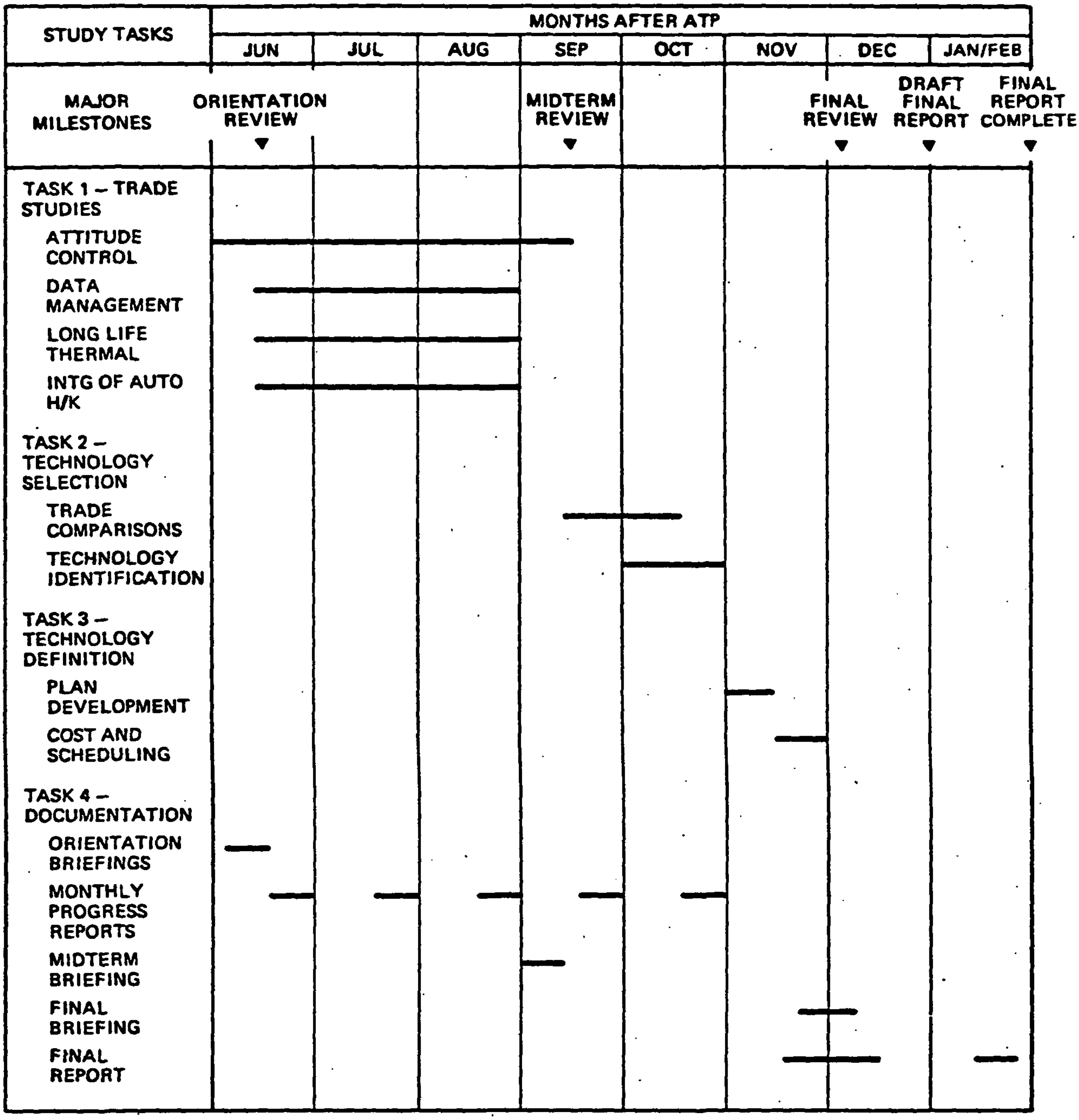


Figure 1.0-1 Program Schedule

1. Data Management System Simulation Package.
2. Data Management Network Interface Unit.
3. Data Management Network Operating System.
4. Two Phase Thermal - Long-Life Pumps.
5. Two Phase Thermal - Heat Exchanger.
6. Two Phase Thermal - Two-Phase Water System.
7. Integrating Controller for Space Station Autonomy using Expert Systems.

This volume presents the technical work performed to select these high-leverage items. The total final report is made up of this volume, Volume I: Executive Summary, and Volume III: Technology Advancement Program Plan.

2.0 ATTITUDE CONTROL

2.1 INTRODUCTION

2.1.1 Objectives

The objective of the study was to initiate the development of technologies required for the solution of the control-structure interaction problem in space station design. The approach was to determine through analysis and simulation the degree to which non-interacting low-band controller technology is applicable to attitude regulation of a space station with large flexible solar arrays. Primary emphasis was given to identifying the limitations of low-band controller technology for flexible space station applications. Passive and active control technologies were to be reviewed as potential improvements to the damping provided by a low-band controller in the event that attitude stability and performance were unacceptable.

The term low-band control is somewhat misleading in the present context. The application of low band design usually implies a band limiting of the control signal. In the presence of significant structural interaction with the core station band limiting the control signal eliminates a significant portion of the attitude error information contained in the output. In this study all the available attitude information, including flexible effects measured by a sensor package mounted on the core station, is passed to a linear actuator that attempts to control the attitude about the center of mass. The sensors are assumed to measure attitude and its rate about three body axes. The measurements are ideal to the degree that the sensors are assumed to be error free with infinite bandwidth. The linear actuators were modeled as ideal control moment gyros (CMG). The low-band controller will therefore attempt to regulate attitude in the presence of induced disturbance torques due to flexibility without actively controlling the motion of the flexible elements. The control system is said to be reactive rather than active in the sense that the core mounted controller reacts to external disturbance rather than actively influencing the disturbance source resulting from appendage flexing. It will be demonstrated that a core mounted linear ideal controller is stable in the presence of flexibility and will provide significant damping of most of the major structural modes. However, some of the modes cannot be controlled with a core mounted controller. The important question is the amplitude to which the controlled modes are excited and the implications of sustained vibration of the associated structural members.

The objectives of the study tasks are described as follows.

1. Evaluate the stability and performance of reactive CMG control laws for impulsive internal disturbances during productive work periods as the space station evolves. The worst case impulsive disturbances are assumed to originate from crew activity and mechanical equipment. The open loop response of the structure to docking loads is also evaluated.

2. Suggest methods of improving the pointing performance by passive damping techniques. A secondary task objective is to determine alternate methods to obtain active damping of structural modes by prudent placement of actuators and motion sensors.

2.1.2 Issues

The principle issues that impact the development of an automatic flight control system for space station are related to the interaction between the control system and structure.

Tight pointing accuracy requirements produce associated requirements for increased control system bandwidth. As controller bandwidth increases, many structural modes will be included within the controller passband. Active stabilization of these modes without sacrificing pointing accuracy is a major issue. Adapting to variations in mode shapes and frequencies caused by space station configuration changes is also a major issue when active damping of structural modes is required. In an effort to reduce control system complexity, the development of passive techniques for structure mode damping is a significant issue. Structural stiffness and damping characteristics are, therefore, crucial to control system design, and early attention must be given to configuration options that increase modal frequency and damping.

Avoiding the interaction of control system and structure is an attractive alternative. The reactive controller achieves this objective with an attendant reduction in control system complexity. The important issue is the controllability of the structure and the resultant lightly damped response to be expected from a reactive controller.

2.1.3 Advanced Platform Systems Technology Study Background

This study is the continuation of the Advanced Platform System Technology Study. The purpose of APSTS was to initiate the control and structure interaction study at the top level. The goal of APSTS was to establish guidelines for flexible space station attitude control system design and to indicate viable technology options requiring further study. In the process of setting guidelines for control system design, APSTS intimated that low-band controller pass band would be limited to frequencies less than .10 Hz and most likely less than .01 Hz owing to the lowest solar array structural mode frequency. It was feared that if the free-free mode control bandwidth interacted with the flex mode dynamics, instability would result. Therefore a cutoff well below the lowest flex mode frequency would ensure stability with a performance penalty. However, the results of this study clearly show that flex mode stability is not an issue of concern when a reactive controller is used. Rather, the principle concerns with reactive control are the presence of structural modes with essentially no damping augmentation from the controller and the implications that accompany the sustained vibrations as previously mentioned. This study shows that the magnitude of undamped modal vibration can be reduced by increasing the system bandwidth. However there are obvious limitations owing to the accuracy which attitude can be determined. These issues will be discussed in the sections to follow.

2.1.4 Overview

In the following sections the technical approach to the analysis and simulation tasks along with a summary of the results and conclusions will be given. Section 2.2 presents the details of the technical approach used to conduct the study. First, a brief summary of the configuration selection process will be given. Then the subtasks will be outlined. Finally, the architecture of the software used for analysis and simulation of the selected configuration will be presented. Section 2.3 presents a detailed discussion of each of the elements effecting the attitude control system design. The elements include the structure, controllers, disturbance inputs, and feedback control laws. A stability analysis of the closed loop system is presented, and the results are correlated with simulated time response data. Section 2.4 summarizes the results of the analysis and simulation tasks. Section 2.5 presents the conclusions of the study, and section 2.6 gives recommendations for continuing effort in the identification of technologies for space station attitude control. Section 2.7 provides a list of references.

2.2 APPROACH

The technical approach is formulated in terms of five main tasks. These tasks are described in the discussion to follow.

2.2.1 Formulate a Candidate Configuration

The major elements required to formulate a candidate space station architecture are the class option categories, the functional attributes as defined by NASA and the set of governing assumptions. Class option categories refer to the premises that define the architectural concept. The two categories are the open class and the limited class. The premise for the limited class is "a space station as a permanently inhabited facility engaged in productive work and delivered to low earth orbit in stages the dimensions of which are consistent with the shuttle cargo bay". The open class consider applications such as the use of the shuttle external tank, shuttle derived launch vehicle and tethers.

The first step in the process was to select a class option. The configuration for the space station technology study was derived from the limited class premise with adherence to NASA governing assumptions. The details of the configuration selection process along with the set of NASA assumptions and groundrules are given in section 2.7, reference 1.

The next step was to develop a schematic architecture consistent with the functional attributes and incorporating various strategies for growth leading to a 12-man configuration representative of shuttle deliverable hardware.

The result was an evolutionary configuration that is controllable and functional as a space station. The attitude control study considered four operational stages that incorporate two phases of assembly, with and without the orbiter docked. The two phases of assembly will include the initial habitable stage and the all-up fully operational stage.

A pictorial view of the study configuration is shown in figure 2.2-1. A representative buildup sequence is shown in figure 2.2-2 along with the stages selected for analysis. The weight of the all-up configuration is 94000 kg with solar panels sized for 75 kW

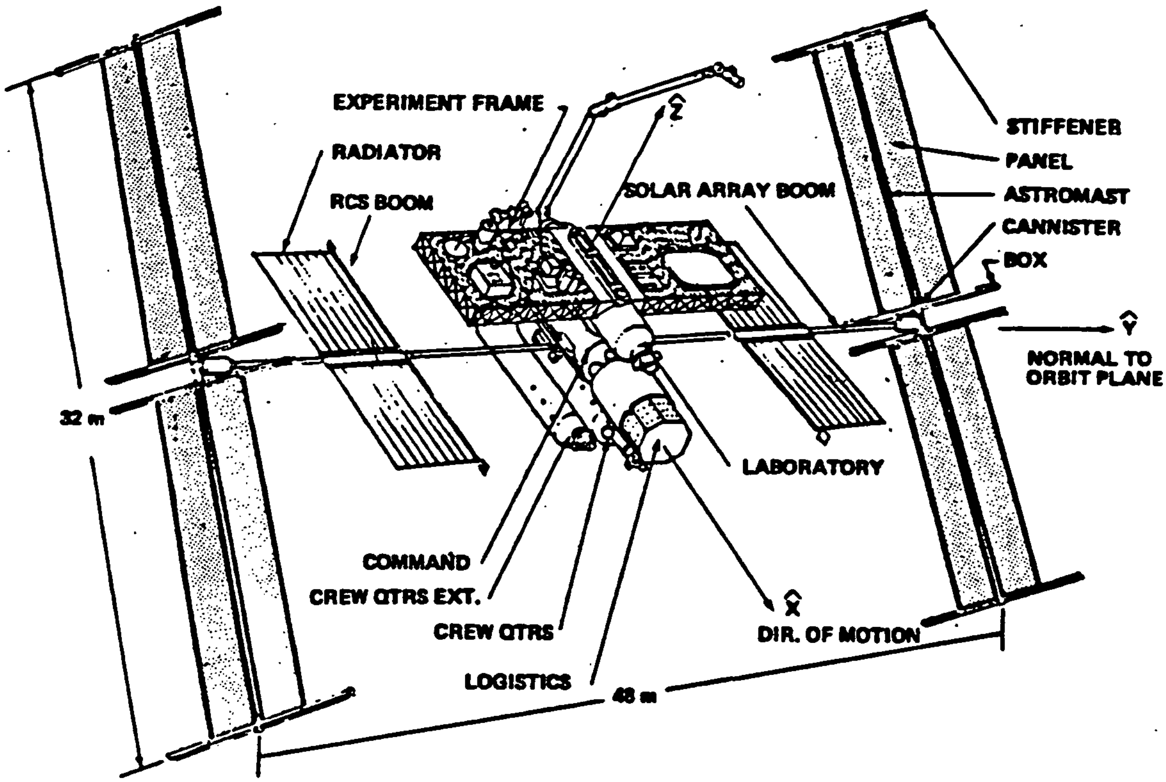
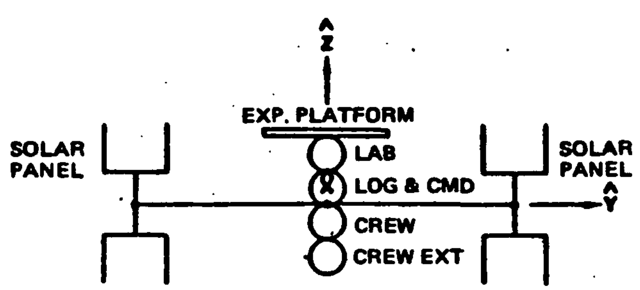


Figure 2.2-1. Space Station Balanced Array Concept with Astromast Solar Array Deployment



CONFIGURATION ①

LOGISTICS + COMMAND + CREW QUARTERS + SOLAR PANELS

FIRST HABITABLE CONFIGURATION

CONFIGURATION ②

CONFIGURATION ① + REMAINING MODULES

ASSUMES NO OTV OR PROPELLANT TANKS

Figure 2.2-2. Buildup Sequence Defining Configurations for Control/Structural Analysis

(actual). The total surface area of panels for 75 kW is 1100 square meters. The inertial and structural properties of the configuration will be presented in section 2.3.

Initial configurations featured a cantilevered solar panel design, where the entire panel was pivoted at the end point. As the configuration developed the center pivoted balanced solar array concept was proposed as a configuration improvement for enhancing attitude control. The issue of achieving controllability through mass balance was the primary concern in the configuration of the center mounted solar panels. Mass balance was a principal design goal in order to ensure that CMG controllers will enable attitude stabilization with minimal expenditure of energy for momentum management. Dynamic balance is achieved by center pivoting the solar panels. The balanced configuration considerably reduces dynamic products of inertia for earth pointing that arise as the panels are tilted and rotated to track the sun line. Rotation of cantilevered panels induces very large periodic products of inertia at orbit frequency that create secular torques due to gravity gradient and Euler coupling. The center mounted solar panel also increases the lowest frequency structural mode by a factor of two, due to halving the length of the solar panel deployment mast.

2.2.2 Determine Mass and Dynamic Properties

A finite element model of the station was developed and the resulting mass and stiffness distribution of the structure was input to the NASA Structural Analyzer (NASTRAN). The output modal data from NASTRAN established the normal mode shapes and natural frequencies of vibration.

2.2.3 Define Models for Simulation

The second order equations of motion describing the forced vibration of the structure were cast in modal form using the mode shapes and frequencies from the NASTRAN model. Ideal CMG controllers and rotational motion sensors were colocated on the space station near the mass center. The controller configuration, torque distribution algorithms, and feedback control laws along with a model of the internal disturbance torque from crew activity will be described in section 2.3.

2.2.4 Develop Program Architecture for Simulation and Analysis

The system of analysis programs for control and structure interaction analysis and simulation is shown in figure 2.2-3. The IAC (Integrated Analysis Capability) provides I/O data manipulation and storage for all major system elements in an automated and interactive fashion. The major system elements are NASTRAN, optimum regulator and control of linear systems (ORACLS), and engineering analysis system (EASY). The synthesis of a controller for a flexible structure would proceed as follows. First, NASTRAN computes the flexible dynamics of the vibrating structure in terms of normal mode shapes and frequencies from a finite element model of the space station mass and stiffness distribution. Next, interface program INDA formats the NASTRAN dynamic model output for input to ORACLS. Programs using ORACLS subroutines generate the linear state space formulation of the rigid and flexible body dynamics along with the sensor output matrix that relates the sensor outputs to both rigid and flexible state variables (sec. 2.7, ref. 2). The system dynamics and sensor output matrix are then used in the design of attitude control regulator and feedback compensators in the time domain, using Linear Quadratic Gaussian synthesis. The feedback gain matrices computed from ORACLS routines along with the disturbance torque model and the system and sensor output matrices from ORACLS subroutines are input to EASY 5. Program EASY 5 is an engineering analyses system that computes the time response of a nonlinear system and has the capability of linearizing the nonlinear system about an operating point for the purpose of stability assessment and other linear time and frequency response analysis tasks.

It is noted that the IAC was a pivotal factor in the successful completion of this work. High order models require very large data files that must be manipulated to effect controller design and analysis. Data and model files must be stored and retrieved for performance analysis and graphics presentation. In the absence of a fully automated interactive I/O capability, the analysis and synthesis tasks of designing controller for realistic structural models is precluded.

2.2.5 Conduct Analysis and Simulation

The analysis of attitude control system stability was performed by arguments based on the theory of positivity of operators (sec. 2.7, refs. 8 and 9). The basic stability theory was verified by frequency response methods and time response from simulation of the

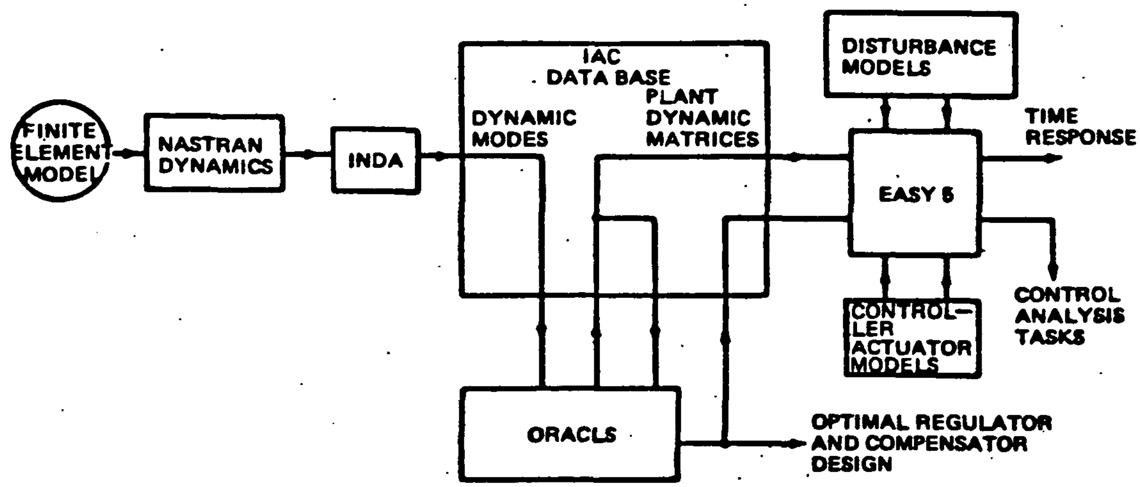


Figure 2.2-3. Software Architecture Technical Approach for Dynamic Simulation and Analysis

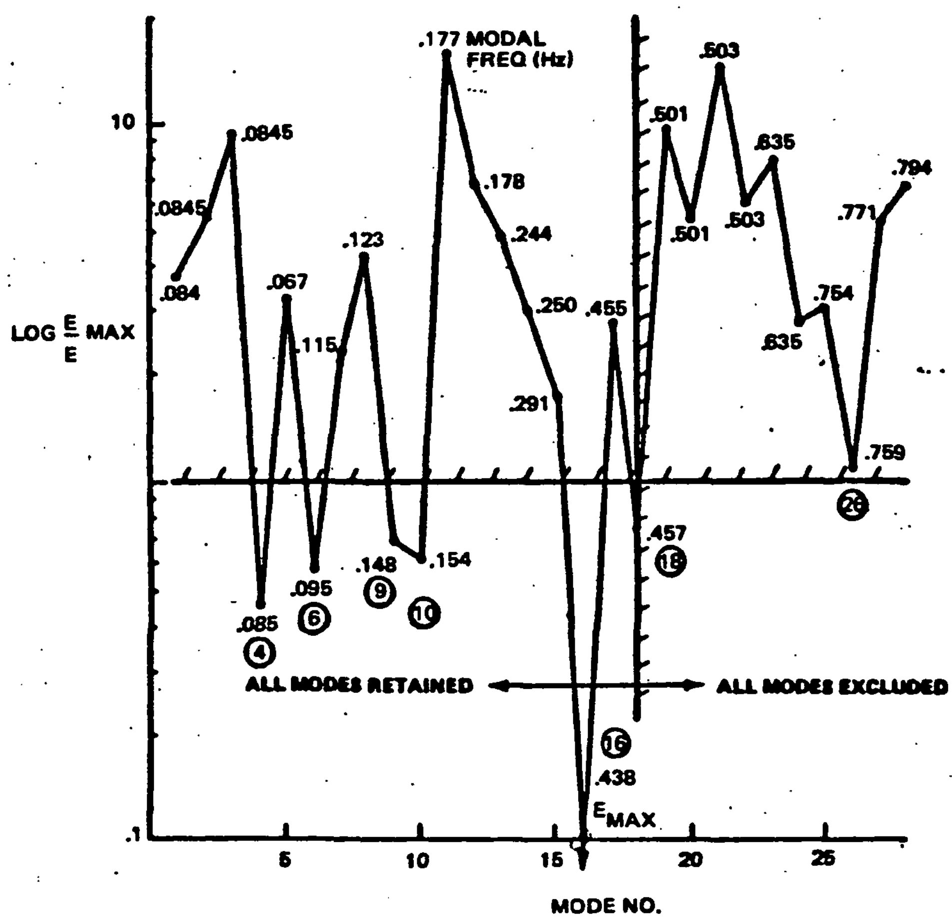


Figure 2.3-1. Modal Reduction of Structure Model by Impulse Energy

closed loop system. The performance of the closed loop system was determined from time response data. System performance includes the motions of the central core and the flexible elements. Stress at the root of the solar array boom and astromast were derived from time response data. These calculations are especially valuable for evaluating structural integrity due to docking loads.

2.3 TECHNICAL DISCUSSION

2.3.1 Structural Model

A finite element model was constructed using the NASTRAN computer program. The following is a description of the model. All components described are labeled in figure 2.2-1. Section properties and dimensions are shown in table 2.3-1.

2.3.1.1 Solar Arrays

The solar array booms were modeled as graphite/epoxy tubes, 24 meters long. The solar array astromasts were modeled as triangular trusses with a design by AEC-ABLE called Continuous-Longeron Able Boom. Sizing of the boom and astromast was done assuming a maximum static load of 0.1g. The astromasts are housed in round cannisters at the end of the array boom. The solar array panels are stored in boxes at the near end of each panel and reinforced at the outboard end by a stiffer. Rods extend from the box to the stiffener along the center of each panel to simulate the cable along which the panel is deployed.

2.3.1.2 Modules

The five modules were assumed to be rigid bodies with flexibility at their connection points with each other and with the orbiter. The stiffness at the ends of the modules was computed separately for the module and for the docking tunnel, then springs in series were assumed and the stiffness for the module including the docking tunnel was computed. The stiffness at the module side connection points was computed using equations for circular rings.

2.3.1.3 Mass Properties

The mass properties of the space station were derived under the following assumptions. The masses of all the structural members are uniformly distributed along their lengths. The masses of the solar panels are lumped half at either end of the astromasts and mass

Table 2.3-1. Flexible Element Section and Material Properties for Space Station

MEMBER	NASTRAN ELEMENT	DESCRIPTION	MATERIAL	$A(m^2)$	$I(m^4)$	$J(m^4)$
Array Boom	Bar	Tube d = .381m t = .0025m	GR/EP	2.99E-3	5.43E-5	1.09E-4
Astromast	Bar	triangular truss d = 9.E-3m h = .3m	6-GL/EP	1.91E-4	3.82E-6	3.82E-6
RCS Boom	Bar	Tube d = .254m t = .0005m	GR/EP	3.99E-4	3.22E-6	6.44E-6
Cannister	Bar	Tube d = .302m t = 7E-4m	GR/EP	7.08E-4	7.57E-6	1.51E-5
Box	Bar	Tube d = .13m t = 5E-4m	GR/EP	2.03E-4	4.22E-7	8.44E-7
Stiffener	Bar	Tube d = .1m t = 5E-4m	GR/EP	1.56E-4	2.1E-7	4.2E-7
Cables	Red	Cable d = .001m	CELION	7.85E-7	NA	1.E-11

Material Properties

Celion Fiber Cables	$E = 172E9\ N/m^2$	
S Glass/Epoxy	$E = 52E9\ N/m^2$,	$G = 6E9\ N/m^2$
Graphite/Epoxy	$E = 108E9\ N/m^2$,	$G = 15E9\ N/m^2$

moments of inertia are added to reflect the actual mass distribution. The module masses are lumped at their c.g.'s with moments of inertia to reflect the actual mass distribution.

The mass of the radiators was lumped along the boom at either end of the radiator with moments of inertia included to reflect the actual mass distribution. The mass of the RCS thrusters was lumped at the outer end of each RCS boom.

The space station mass properties for the test configurations with and without the orbiter docked are given in table 2.3-2. The principal axis basis vectors are the columns of matrix M.

From the parameters given in table 2.3-1 and the dimensions shown in figure 2.2-1 the stiffness of the members in torison and bending can be computed from the relations,

$$K_{tor} = \frac{GJ}{L}$$

$$K_{flex} = \frac{3EI}{L^3} \quad \text{(concentrated load at } x = L\text{)}$$

where G and E are the moduli of rigidity and elasticity, J and I are the axial and transverse area moments, L is the length of the structural member, and A is the cross sectional area.

The stiffness equations for torsion and bending in table 2.3-1 were used to estimate the frequency and amplitude of oscillation for the elastic members as a check on the NASTRAN model.

2.3.2 Structural Model Order Reduction

The order of structural model derived by finite element methods is theoretically infinite. In a practical sense the model is very large, the majority of the modes having negligible inpact on controller design.

Table 2.3-2. Mass Properties of Space Station

Quantity	Configuration 1	Configuration 2	Configuration 2 + Orb	Units
I_x	1.43	2.85	16.22	
I_y	1.48	3.32	2.546	$Kg\text{-}m^2 \times 10^6$
I_z	2.51	3.00	12.55	
I_{xy}	0	0	0	
I_{xz}	.122	.36	-6.791	$Kg\text{-}m^2 \times 10^6$
I_{yz}	0	0	0	
m(2)	53444	94011	191, 681	Kg
(1) x_{cg}	1.38, 0, .628	1.38, 0, .628	-7.66, 0, 9.52	meters
i_p	2.53, 1.48, 1.42	3.30, 3.32, 2.55	7.35, 25.46, 21.42	$Kg\text{-}m^2 \times 10^6$
M	$\begin{matrix} .111 & 0 & .994 \\ 0 & 1 & 0 \\ -.994 & 0 & .111 \end{matrix}$	$\begin{matrix} .632 & 0 & .774 \\ 0 & 1 & 0 \\ -.774 & 0 & .632 \end{matrix}$	$\begin{matrix} .608 & 0 & .794 \\ 0 & 1 & 0 \\ -.794 & 0 & .608 \end{matrix}$	non dim

NOTES

(1) cg location with respect to node 100, the attach point of the solar panels, cf fig. 2.3-9.

(2) The total mass of the solar panels is 1652 Kg.
The total area of the solar panels is 1111 m^2.

To provide ease of analysis and data handling the high order structural model must be reduced. The goal is to isolate those eigenvalues that have the greatest influence on the structure input/output response. The method of impulse energy (sec. 2.7, ref. 3) is found to be effective in reduction of high-order models. The foundations of the theory for the impulse energy method are presented here.

Given a high-order, linear, time invarient, asymptotically stable system in modal form,

$$\dot{x} = Ax + Bu$$
$$y = Cx$$

Simultaneously introduce unit impulses of the form u = δ (t) into all controls. Compute the output impulse response energy.

$$E = \int_0^{\infty} y\ (t)\ y(t)dt = E\ (\lambda_1, \ldots, \lambda_n)$$

For each eigenvalue λ_k of the system matrix A compute the individual contribution $E_k(\lambda_k)$ to the total energy E. The eigenvalues λ_k with the largest E_k are usually retained for model reduction. The impulse energy analysis for the space station structure in configuration 1 is shown in figure 2.3-1. The analysis considered the presence of 80 modes of vibration up to 30 Hz which represents flexing of the raft structure due to compliance at the module interface. The semi log plot shows the relative energy contributions expressed as the ratio (E_{max}/E) for the first 28 modes up to .79 Hz. Values of log (E_{max}/E) for mode numbers greater than 28 are all substantially greater than 1. Based on this analysis, the first 18 structural modes were retained for the simulation model. It is noted that the method of impulse energy gives a clear indication of those modes that can be affected by the given combination and placement of sensors and actuators.

The mode shapes and frequencies of the truncated structural model for $E_{max}/E < 1$ are shown in figure 2.3-2. These are the modes identified by impulse energy as being the most susceptible to control by core mounted actuators and sensors. The fundamental torsion and bending modes of all structural members are represented. The first astromast bending mode above the fundamental is present in mode 18. It is interesting to note that the highest impulse energy is contained in mode 16. This mode of vibration is *dominated by array boom and astromast bending. From this observation, conclude that* bending of the array boom and astromast are the flexible element motions most efficiently damped by the core mounted controller. Also note that mode 6 appears

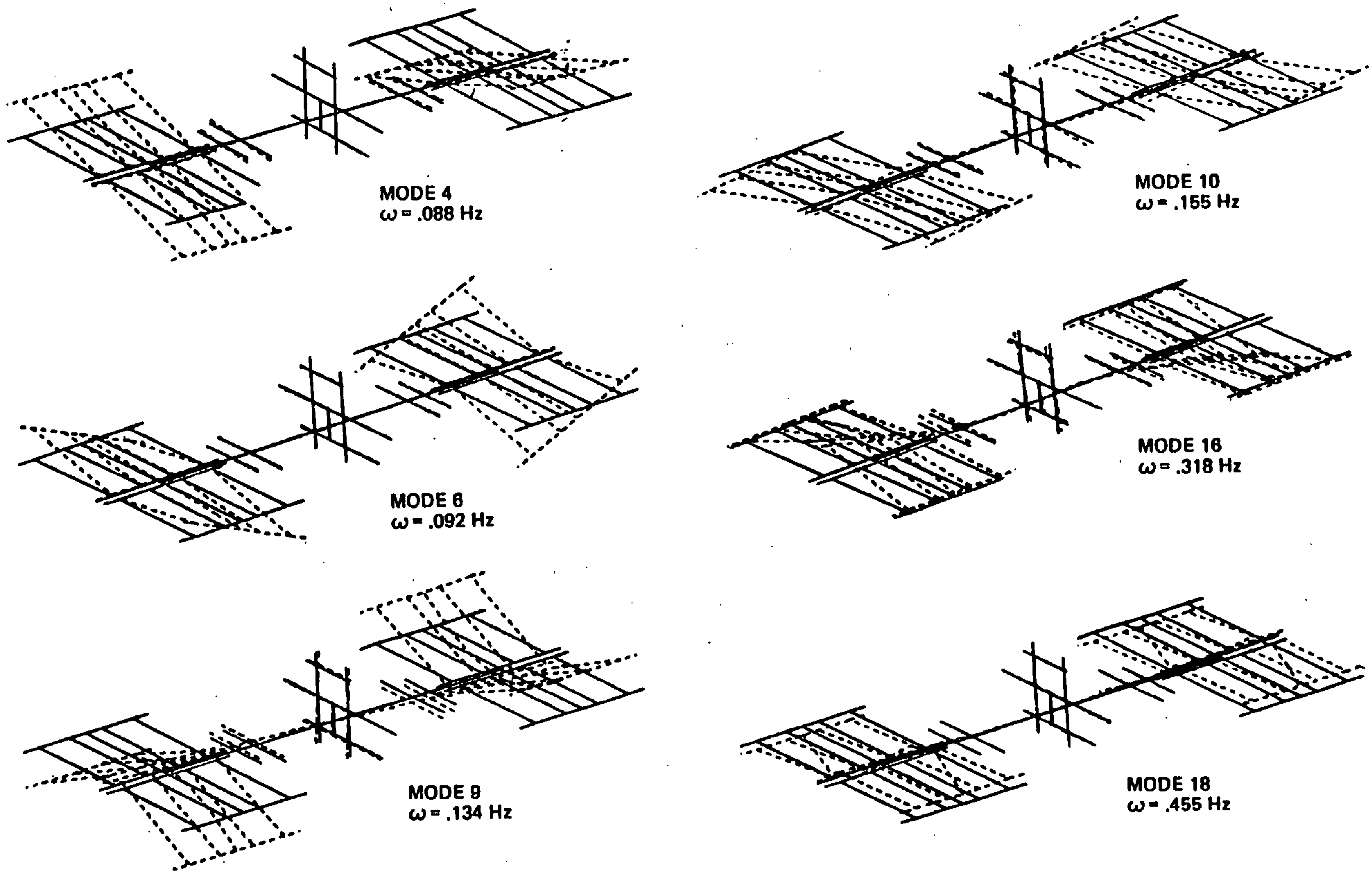


Figure 2.3-2. *Normal Mode Shapes and Frequencies for Modes in Truncated Model with Normalized Energy $E_{max}/E < 1$*

to be dominated by astromast torsion and to a lesser extent by bending. However, from figure 2.3-3 observe that mode 2 (modes 1, 3 similar) is exclusively dominated by astromast torsion. Therefore from impulse energy conclude that the principle energy contribution to mode 6 is from astromast bending and astromast torsion is not controllable with the core mounted actuators and sensors. These conclusions will be verified by the time response of the closed loop control system. It is also clear from mode 6 that bending and torsion are coupled. Therefore a method for actively controlling astromast torsion with core mounted actuators is indicated and will be presented in the discussion of the control response results.

It is noted in passing that the structural model made no mechanical provision for coupled bending and torsion of the astromast section. Recall that all the mass of the solar panels was lumped at either end with inertias included to reflect the mass distribution of a flat plate. Because inertia forces and torques act through and about the center of mass the observed coupling of bending and torsion in mode 6 is a model phenomenon and must not be linked to a direct mechanical cause and effect. Future models of the astromast section will include inertia forces of the solar panels that are offset from the section centroid, producing torsion as the mast bends.

2.3.3 Controller/Sensor Selection

The controllers selected for the space station simulation are a multiple grouping of Skylab class two axis double gimballed control moment gyros in a parallel mounted configuration. A schematic of the configuration is shown in figure 2.3-4. The two axis double gimballed CMG is ideal for applications where rate loop bandwidth is not essential. In this instance there is a greater demand for H than $\dot{H}$ and the two axis gyro approximates a position controller.

The parallel mounting configuration provides a very simple gimbal angle steering law. In addition, hardware mounting, redundancy management, and failure accommodation are greatly simplified. The parallel mounting steering law provides reduced rate requirements on the outer gimbal and avoids singularities internal to the angular momentum envelope. The gimbal angle control laws were taken from reference 4 in section 2.7. For reference, the distribution of gimbal angles and rates for a typical closed loop response to an impulsive disturbance is shown in figures 2.3-5 and -6.

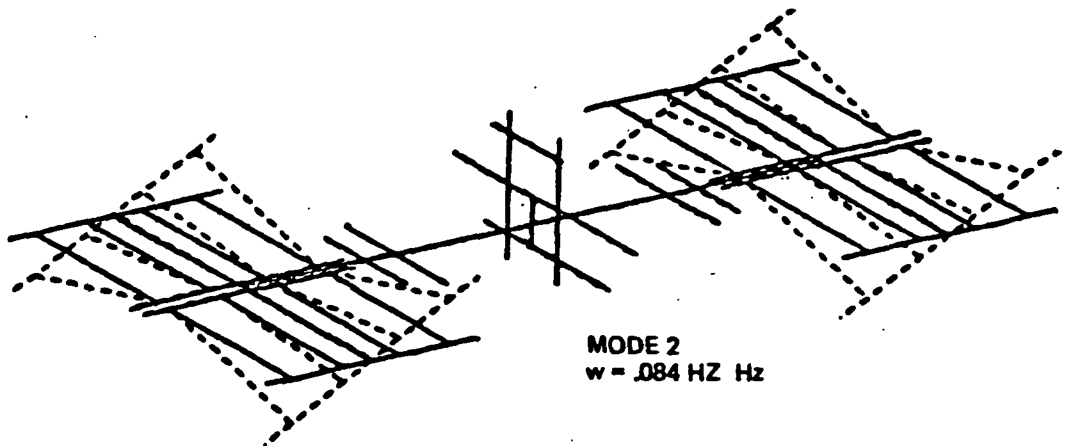


Figure 2.3-3. Second Bending Mode

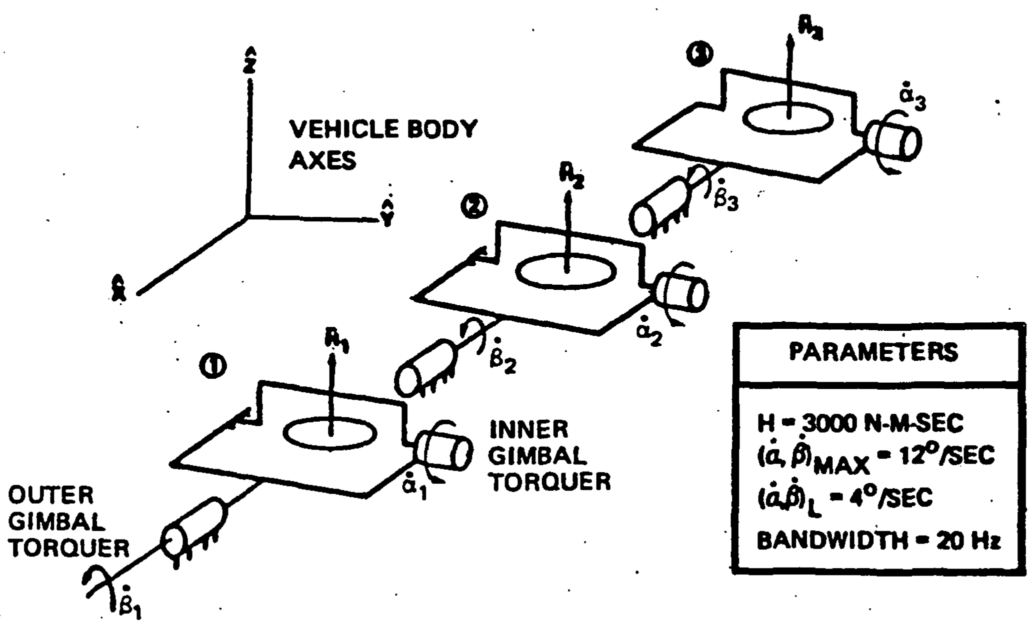


Figure 2.3-4. Three Axis Parallel Mounted CMGs for Space Station

It is noted from figures 2.3-5 and -6 that the initial position of the outer gimbals is such that all H vectors are 120° apart. This distribution produces zero net momentum state in spacecraft coordinates which is advantageous for multiple CMG applications to earth oriented vehicles.

The dynamics of the CMG's were neglected in this analysis because the bandwidth of a Skylab class two axis gyro is approximately 10-20 Hz. The bandwidth of the attitude control system is expected to be less than .50 Hz. The phase contribution from a 20 Hz actuator at rate loop crossover is therefore negligible. The motion variables of the free-free modes (attitude and attitude rate about the center of mass) were assumed to be derived from a measurement algorithm, for example, quaternion integration where the bandwidth of the process can be assumed large with respect to the attitude control system.

2.3.4 Disturbance Input Profile

The disturbance profile for modeling crew activity is shown in figure 2.3-7. The model represents an astronaut in a soaring maneuver within the space station. A detailed description of crew disturbances is given in reference 5 in section 2.7. The motion is envisioned as being a pushoff from one wall and a deceleration at the far wall. The parameters for the motion are presented for a large astronaut in the flight within a module of about 12 ft in diameter. The resulting impulsive momentum disturbance is 400 n-m-sec for each element of the doublet. To establish a highest upper bound from all internal sources including mechanical equipment a value of T_0 = 1000 n-m was used as a worst case value for simulation and analysis.

The worst case level was derived by considering all the internal disturbances from the major sources including crew motion. Table 2.3-3 summarizes the momentum contributions from liquid transfer, rotating equipment and crew activity. An upper bound of 1000 n-m-sec seems reasonable.

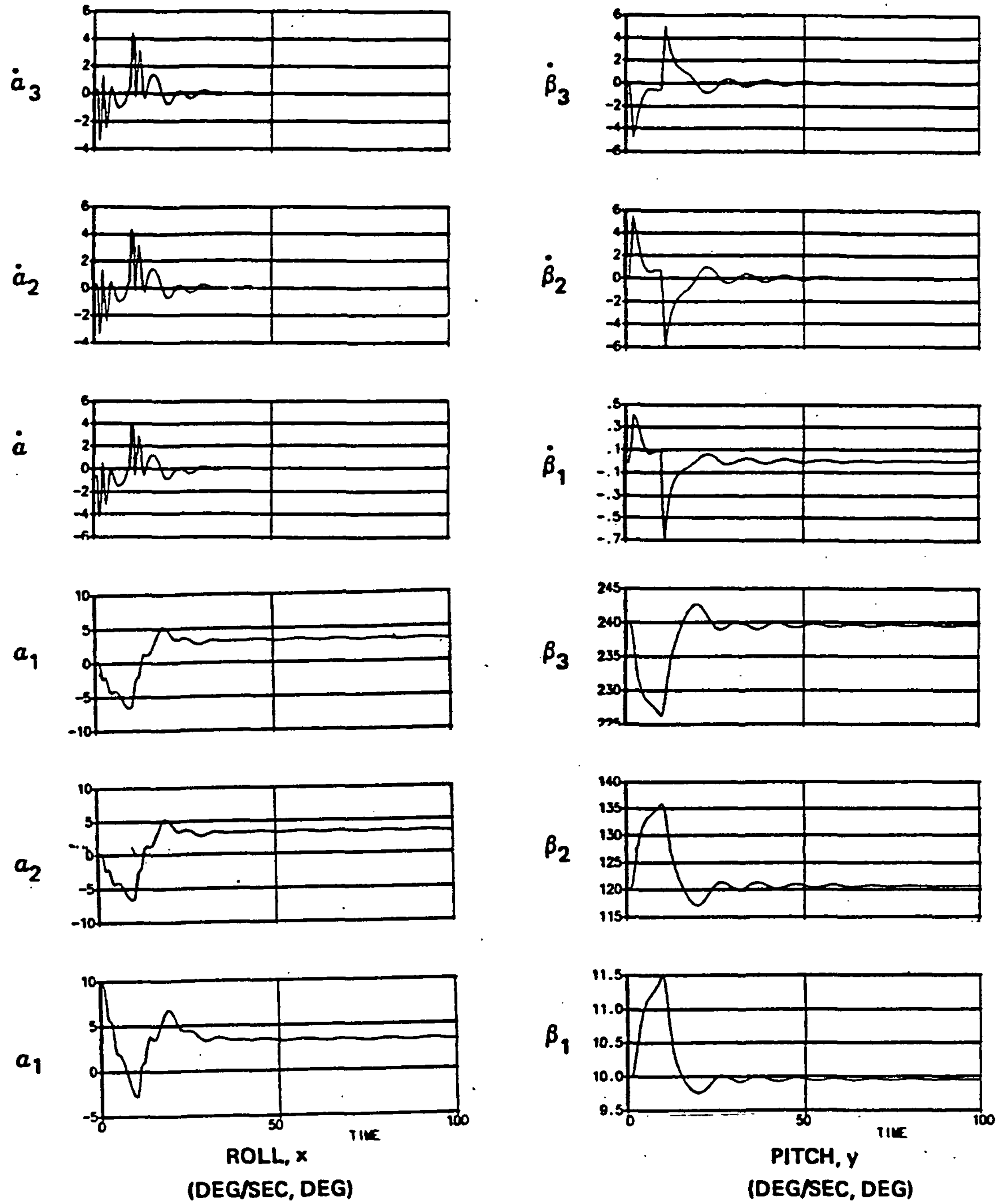


Figure 2.3-5. Closed Loop Controller Response to 1000 N-M-Sec Impulse Doublet in Pitch and Roll for Configuration 1

System Bandwidth = .05 Hz

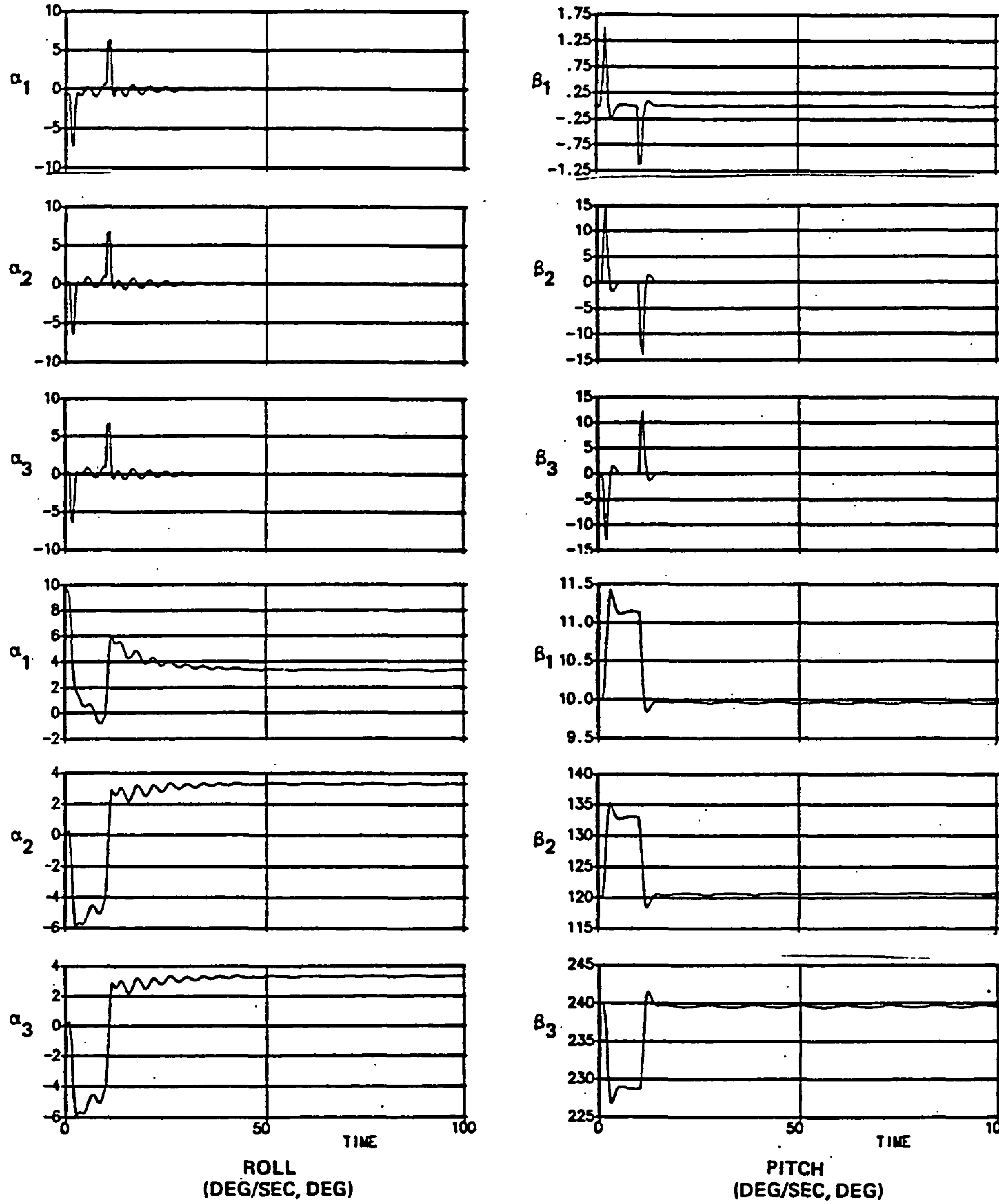


Figure 2.3-6. Closed Loop Controller Response to 1000 N-M-Sec Impulse Doublet in Pitch and Roll for Configuration 2

<u>*System Bandwidth = .25 Hz*</u>

Table 2.3-3 Internal Disturbance

SOURCE	DIST. MOMENTUM (N–m–s)
Liquid Transfer:	
OTV Fuel Transfer	200
Cooling Loop	100
Rotating Equipment:	
CELSS	300-500
Medical	800
Crew Activity	400

2.3.5 Simulation Results

The simulated response of the structure to the single test disturbance impulse doublet was computed for both open loop and closed loop cases. The resulting time responses are shown in figures 2.3-11 to 2.3-16. Figures 2.3-11 to 2.3-14 give open and closed loop responses side by side for easy visualization of the effect of the controller on the disturbed system. The block diagram for the closed loop system representing an attitude regulator is shown in figure 2.3-9. The nodal structure indicating the nodes used to extract measurement data is shown in figure 2.3-8. Motion of the core structure relative to an inertial frame was extracted from the rotational state of the variables ϕ, θ, ψ (roll, pitch, and yaw, about x, y, z) of node 100. Measurements of flexible element motion relative to node 100 are specified as follows. These rotational measurements indicate the flex and twist of the solar panel boom and the astromast structure,

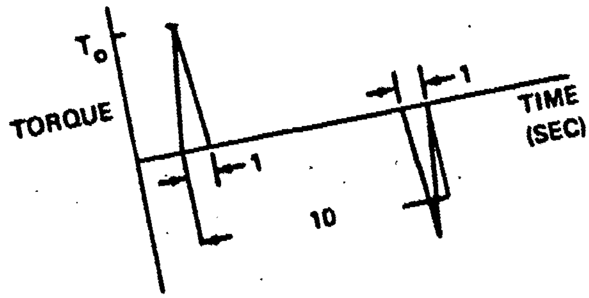
M_{B_x} = Flex of panel boom (ϕ100-105)

M_{B_y} = Twist of panel boom (θ100-105)

M_{B_z} = Flex of panel boom (ψ100-105)

M_{A_x} = Twist of the astomast (ϕ100-323)

M_{A_y} = Flex of the astomast (θ105-323)



- ASTRONAUT PUSH OFF AND FREE FLIGHT
  - CREW MEMBER MASS = 100 KG
  - FREE FLIGHT VELOCITY = .40 M/S
  - PATH CG OFFSET = 01 m 10 m
  - NET DISTURBANCE MOMENTUM H_o = 400 N-M-SEC

Figure 2.3-7. Disturbance Model for Crew Activity

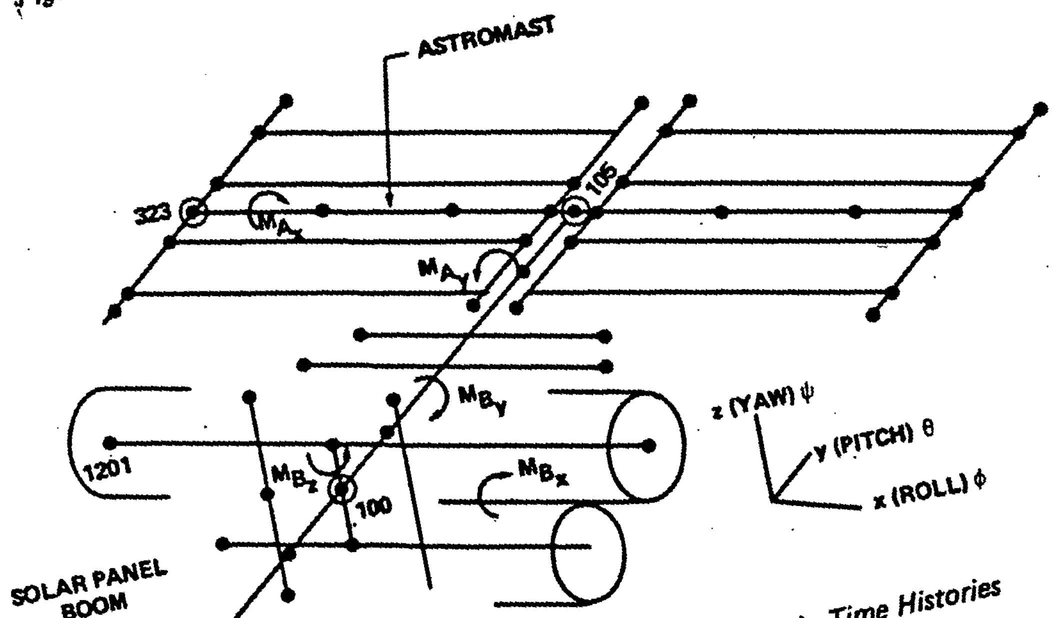
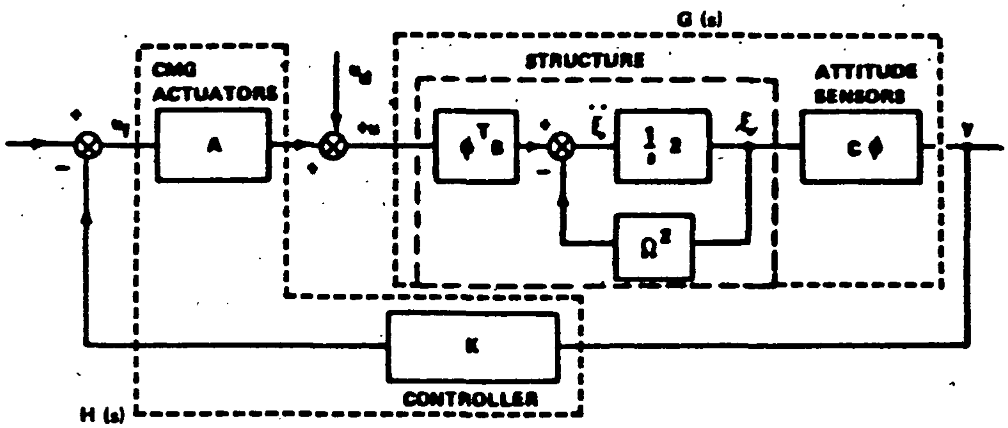


Figure 2.3-8. Measurements of Flexible Elements for Reference in Time Histories



VECTORS			DISTRIBUTION MATRICES		
u	=	TOTAL TORQUE	A	=	CMG TORQUE
ξ	=	MODAL COORDINATE	B	=	CONTROL INPUT
y	=	MEASUREMENT	C	=	MEASUREMENT
f	=	FEEDBACK TORQUE COMMAND	ϕ	=	MODAL STATE (EIGEN VALVE)
			Ω^2	=	EIGENVALUE DIAGONAL
			K	=	FEEDBACK CONTROL

Figure 2.3-9. Generic Block Diagram of an Attitude Regulator for a Flexible Structure

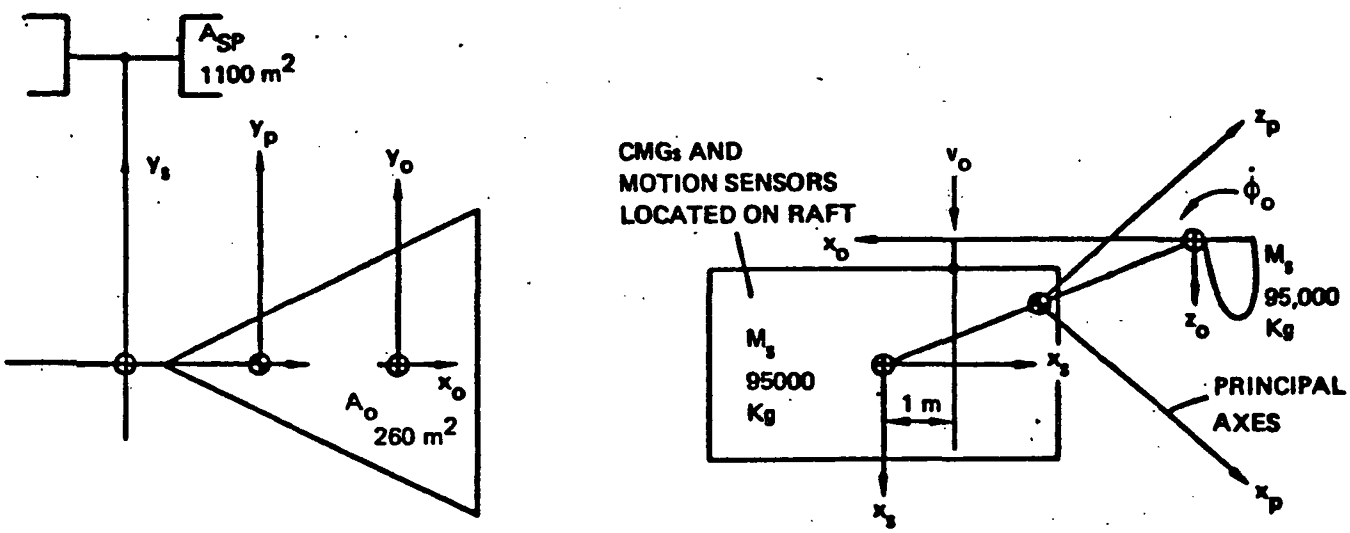


Figure 2.3-10. Orbiter Docking to Space Station Showing Preferred Configuration

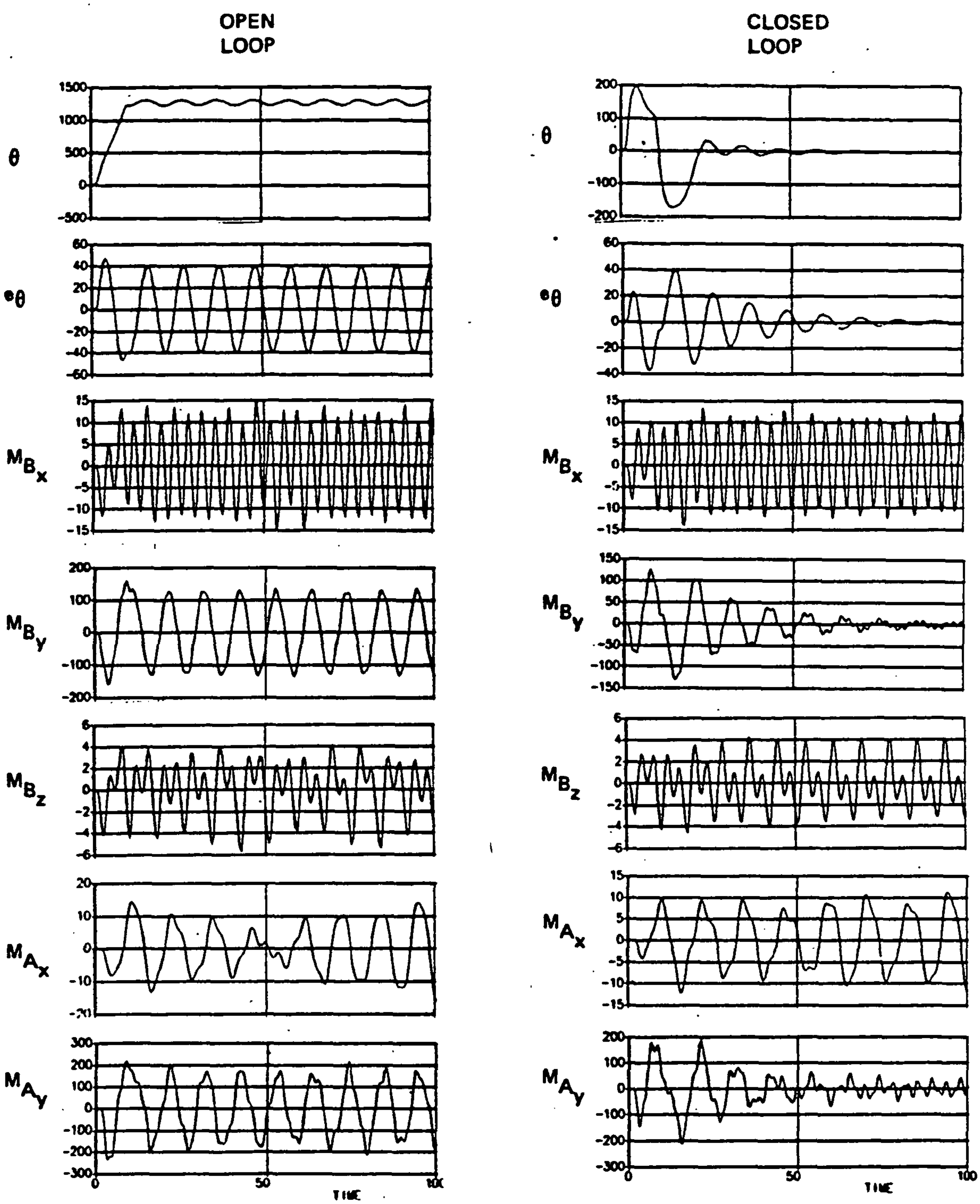


Figure 2.3-11. Response (arc-sec) to 1,000 N-M-Sec Impulse Doublet in Pitch for Configuration 1

System Bandwidth = .05 Hz

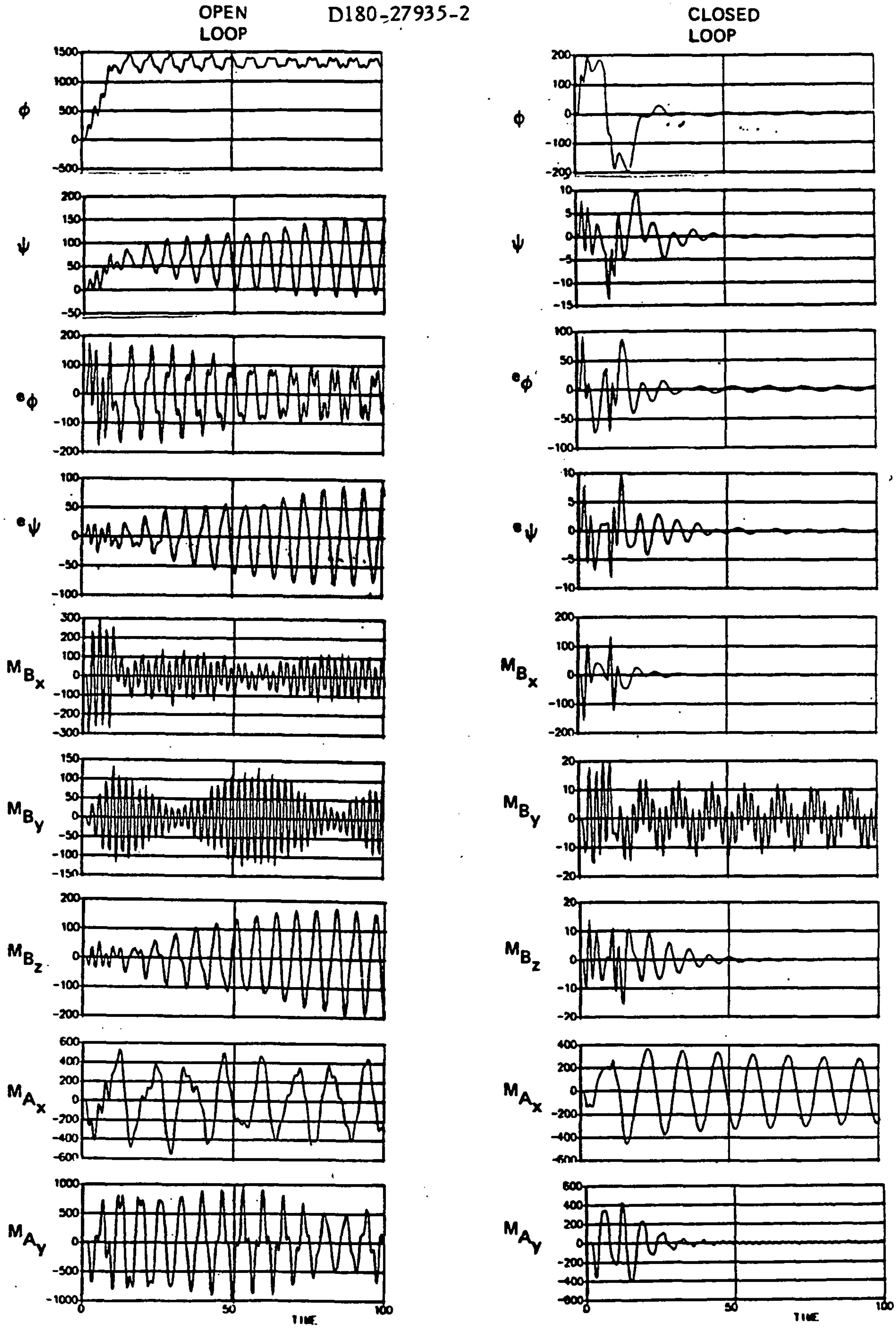


Figure 2.3-12. Response (arc-sec) to 1,000 N-M-Sec Impulse Doublet in Roll for Configuration 1

System Bandwidth = .05 Hz

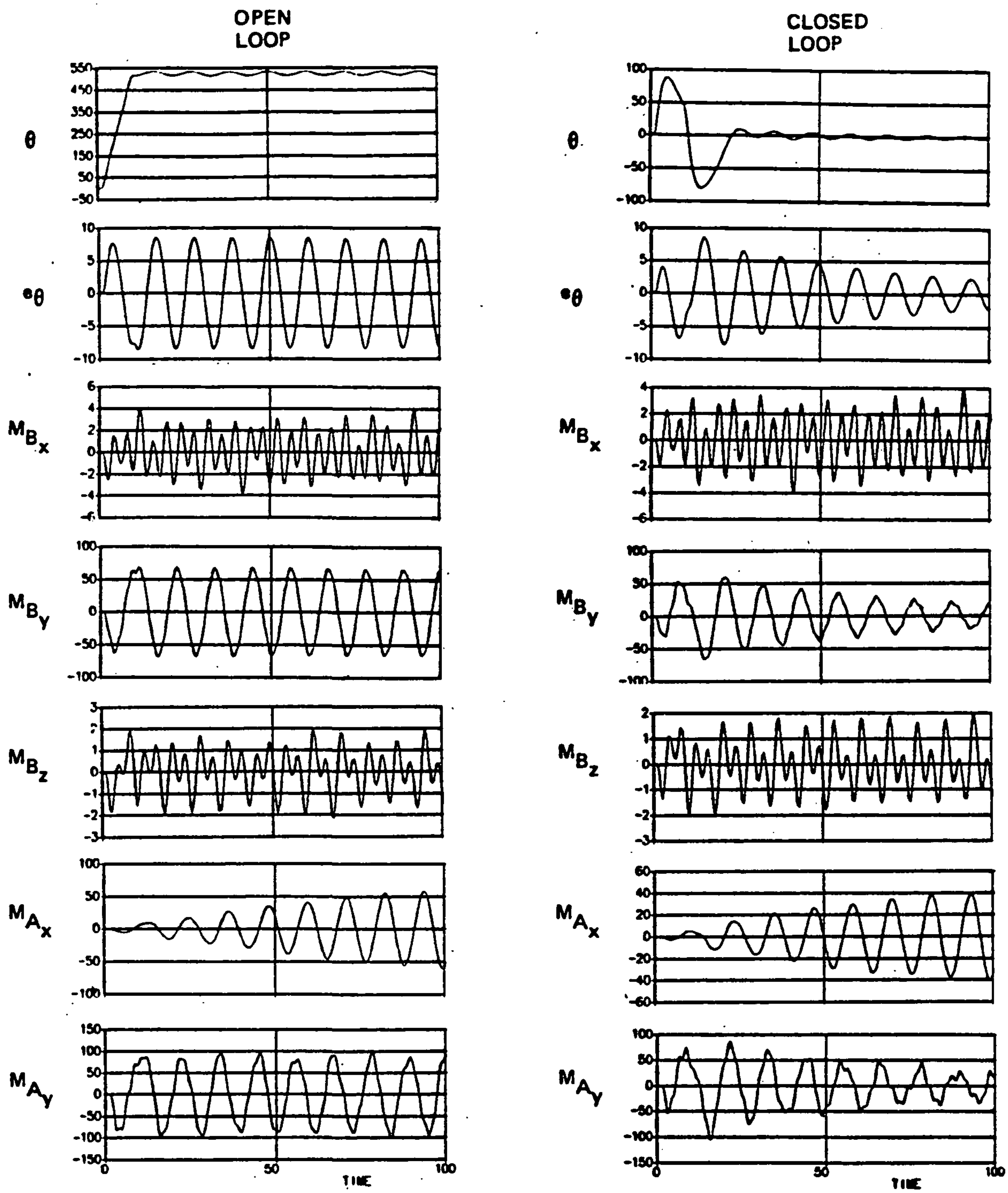


Figure 2.3-13. Response (arc-sec) to 1,000 N-M-Sec Impulse Doublet in Pitch for Configuration 2

System Bandwidth = .05 Hz

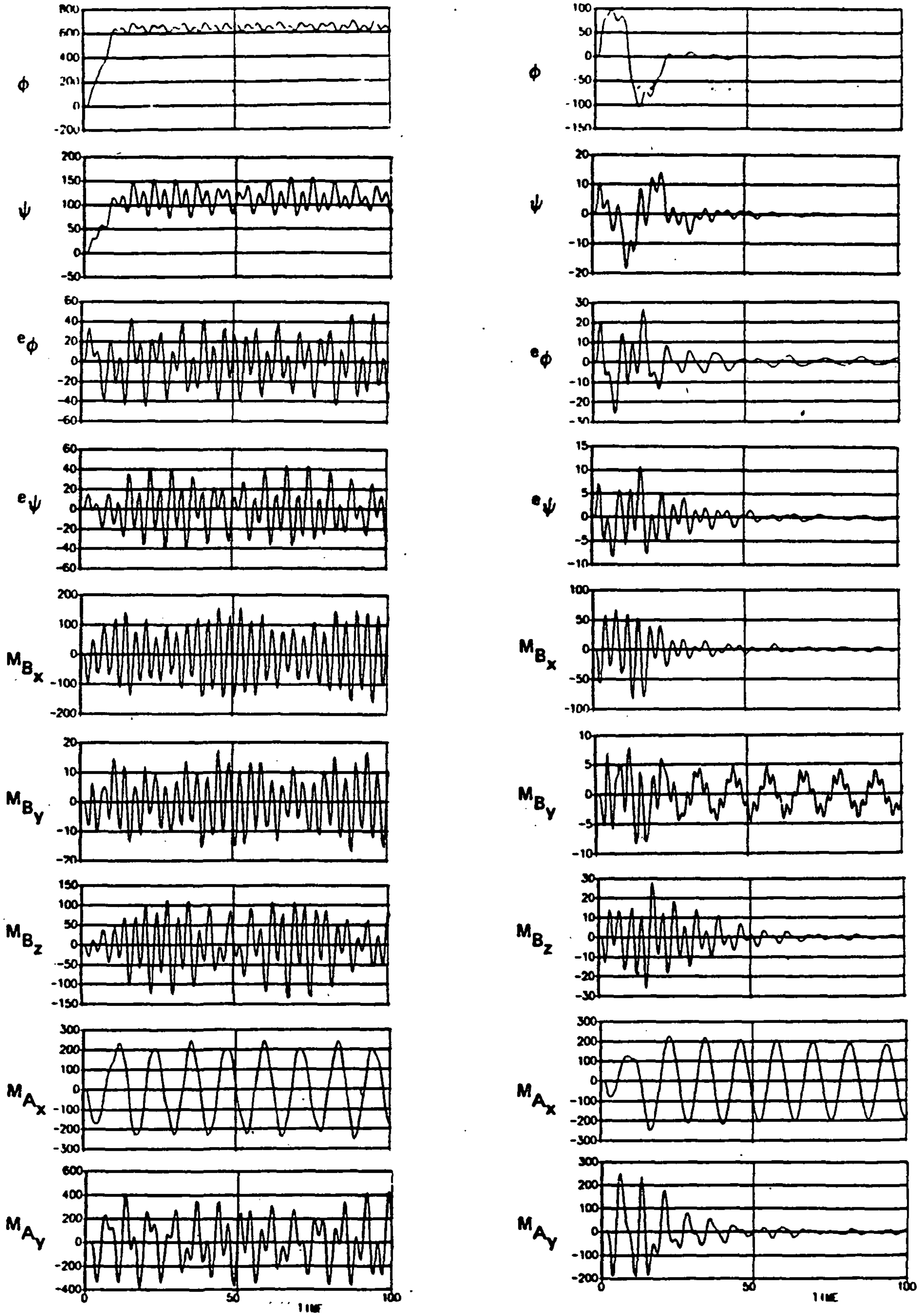


Figure 2.3-14. Response (arc-sec) to 1,000 N-M-Sec Impulse Doublet in Roll for Configuration 2

System Bandwidth = .05 Hz

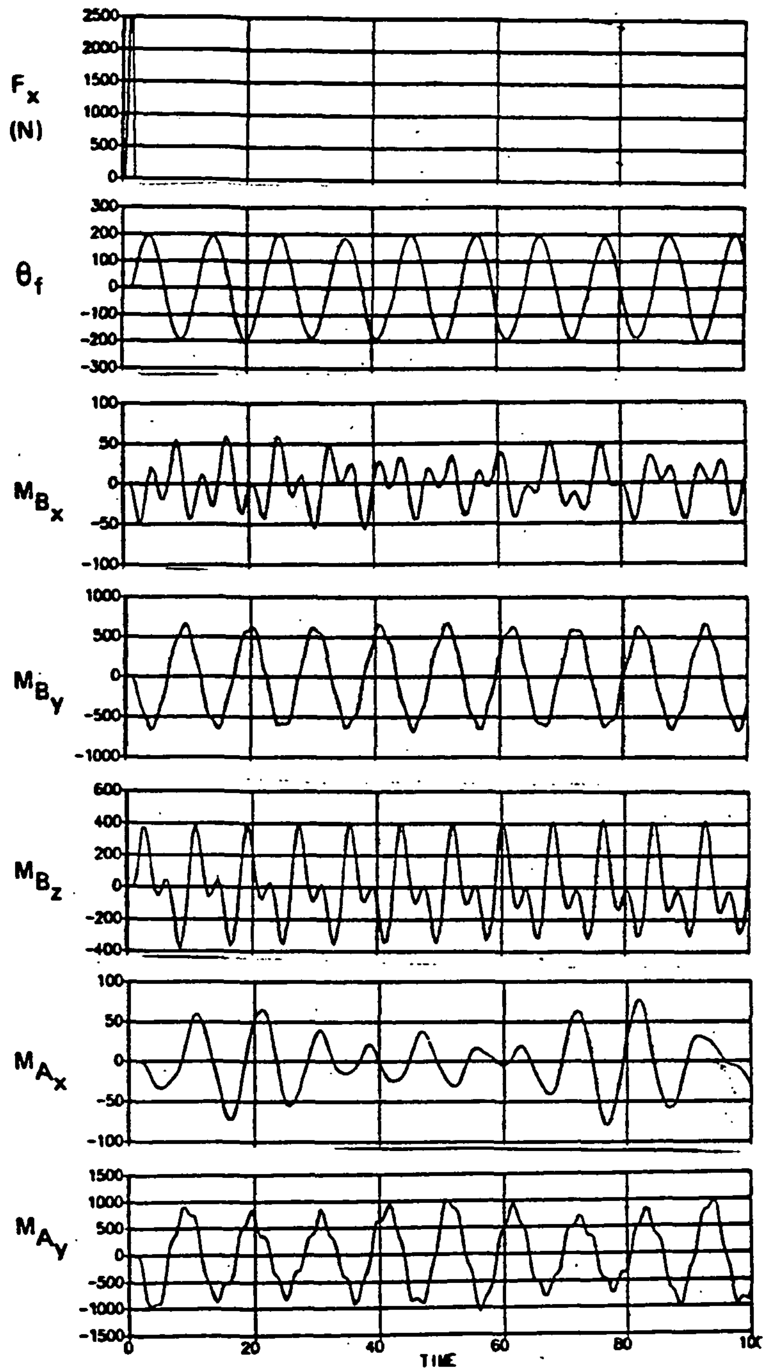


Figure 2.3-15. Impulse Response (arc-sec) of Configuration 1 to Docking Load of 2500 Newtons at Body Station 1201 (Force Along X-Axis)

The quantities $\epsilon_\phi, \epsilon_\theta, \epsilon_\psi$ represent the contribution of the flexible modes to the total attitude response. For example $\theta = \theta_f + \epsilon_\theta$ is the total rotational response of node 100 about the pitch axis and θ_f is the component due to the free - free motion only. It is noted that quantities M_{B_x}, M_{B_z}, and M_{A_y} represent the mode slopes at the end of the associated flexible members. All response quantities in figures 2.3-11 to 2.3-16 are in arc-sec.

2.3.5.1 Open Loop Response

The uncontrolled response of the structure to the test disturbance in the pitch and roll axes is shown in figures 2.3-11, 12, 13, 14 and 15 for configurations 1 and 2. In the pitch axis the contribution of flexibility to core rotation about y, ϵ_θ is dominated by twist of the solar array boom as evidenced by inspection of M_{B_y} and M_{A_y} of figures 2.3-11 and 2.3-13. Reference to figures 2.3-12 and 2.3-14 show that in roll the rotation of the core station due to flexibility, ϵ_ϕ, is attriuted to flexing of the astromast about y as seen in M_{A_y}. The induced bending of the boom, shown in M_{B_z}, is reflected directly into ϵ_ψ. Inspection of M_{A_x} and comparison with $\epsilon_\phi, \epsilon_\psi$ indicates that astromast twist has negligible impact on lateral motions as expected. The coupling of astromast torsion through flexing is clearly seen by comparing M_{A_x} and M_{A_y} for pitch and roll responses. The inertia effect is clearly indicated by comparing the responses for configurations 1 and 2.

The response of the structure to a typical orbiter docking from impact loading at body station 1201 only is shown in figure 2.3-15. It is assumed that the orbiter has an initial rotational rate at docking about its c.g. of $\Phi_o = .2$ deg/sec. with a linear velocity of $V_o = 0.15$ m/sec as shown in figure 2.3-10. assuming the centerline of shock is 1 meter from the station c.g. and further assuming that the collision is perfectly elastic, the resulting impact will impart approximately 2500 N-sec to the station. For the deflections shown in figure 2.3-15, the minimum factors of safety in terms of stress at the beam root are at least 100 in both astromast and array boom bending and torsion.

The max deflection M_{B_z} (figure 2.3-15) was estimated analytically and found to be within 10% of the simulated value. Therefore the simulation was found to be trustworthy giving additional confidence in the interpretation of the modal quantities that are output from the structure dynamic equations computed through the IAC.

2.3.5.2 Closed Loop Response

The simulated response of the attitude regulator to the test disturbance is shown in figures 2.3-11, 12, 13, 14, and 16. The system bandwidth chosen for presentation is .05 Hz for all configurations except .25 Hz for configuration 2. The controller was a simple proportional plus derivative feedback of free - free mode attitude measured at node 100 (see fig. 2.3-8). The time responses indicate that regulated free - free mode attitude is both stable (in accordance with theoretical predictions) and controllable. The controllability of the structure is not surprising because the impulse energy analysis has clearly indicated that controllable normal modes contain motions of all structural elements with the exception of twist of the astromast. The time responses support this claim and would indicate that torsional vibrations of the astomast are not controllable with the controllers and sensors mounted on the rigid core as expected.

Recall from the impulse energy analyses that vibrations associated with antisymmetric mode 16 showed the highest potential for suppression by the core mounted controller. Array boom and astromast bending are the principle components of mode 16 and the time responses clearly show that boom and mast bending vibrations are effectively suppressed. However, although antisymmetric mode 4 shows relatively high impulse energy the torsional vibrations in the boom are not as well damped as boom and mast bending vibrations. Note that the pitch axis response exhibits almost pure mode 4 response. Normal mode 4 is dominated by boom torsion and the mast seems to move as if it were rigid (cf M_{A_y}, M_{B_y}, figs. 2.3-11, -13). Although the flexible state variables associated with this mode are very controllable, they are weakly observable in the output as expected, which accounts for the low relative damping of boom torsional vibrations relative to boom and mast bending vibrations.

It is noted that the rate of suppression of vibration (damping) in the structural elements appears to be independent of vehicle inertia for fixed free - free mode control bandwidth. However, the magnitude of the vibration is of course inversly proportional to vehicle inertia as expected. The damping of structural vibrations for a given vehicle inertia decreases with increasing free-free mode control bandwidth, c.f. figures 2.3-13, -14, and 2.3-16. This is due to the fact that with increasing bandwidth the closed loop modal poles approach the open loop modal zeros that are virtually undamped. The result is that the residual in the response due to a given modal pole is reduced but so is the closed loop damping on that pole.

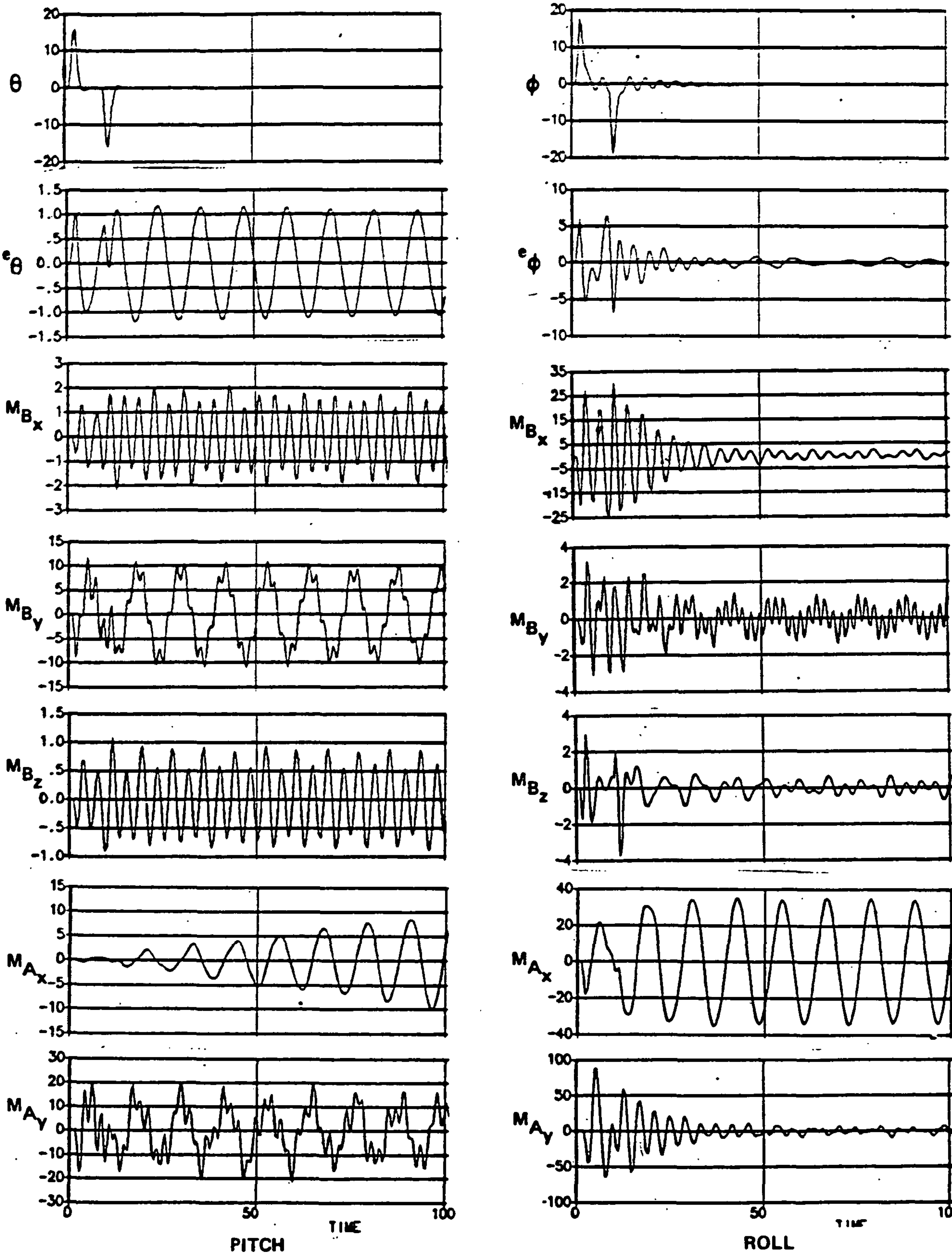


Figure 2.3-16. Closed Loop Response (arc-sec) to 1000 N-M-Sec Impulse Doublet in Pitch and Roll for Configuration 2

System Bandwidth = .25 Hz

2.3.6 Stability Theory

The block diagram for discussing the stability of a structure with colocated sensors and actuator is shown in figure 2.3-8. A formulation of the structure equations and the theorem relating to the nature of the controller required for attitude stabilization is stated here.

Given the undamped structure dynamics in modal form

$$\ddot{\xi} + \Omega^2 \xi = \Phi^T \beta_\mu$$

with state vector $x = \left[\xi, \ \dot{\xi}\right]$, system eigenvalues,

$$\Omega^2 = \left[\omega_1^2, \ . \ . \ . \ . \ , \omega_n^2\right]$$

and system eigenvectors, $\Phi = \left[\bar{\Phi}_1, \ldots \bar{\Phi}_j, \ldots \bar{\Phi}_n\right]$

Given that the feedback is of the form $f = Ky$ where K_p and K_r are the position and rate gain partitions of matrix K.

then, if ideal sensors (C) and actuators (A) are colocated anywhere on the structure then $B^T = C$ and a controller of the form

$$f = \left[K_p \ K_r\right] \begin{bmatrix} \beta^T \Phi & 0 \\ 0 & \beta^T \Phi \end{bmatrix} X$$

stabilizes the attitude of the multi-input, multi-output structure. The gain of the CMG torque distribution matrix is unity. Ideal sensors and actuators have no phase associated with their operation and are said to have infinite bandwidth. The theorem is proven for single-input, single-output system in section 2.7, reference 7 and was derived generally for the multi variable case using positivity arguments from references 8 and 9 in section 2.7.

2.4 SUMMARY OF RESULTS

The important control/structure interaction issues for a representative space station configuration have been addressed. Specifically, the stability and performance of the station with a core mounted linear controller has been investigated. The inertias are of order 10^6 with solar panel size of $1100m^2$ which is consistent with a 75 kW power requirement. The following statements summarize the results of the study.

1. Analysis has shown and the simulation has verified that the raft configuration is stable and controllable when ideal sensors and CMG actuators are colocated. Because the raft is rigid at frequencies of interest (0.5 - .5 Hz), colocation of ideal sensors and actuator on the raft will guarantee stability.

2. Damping of the structural modes is substantially augmented in most cases by the CMG core mounted controller. Damping of astromast torsional vibrations is not augmented by the core mounted controller.

3. The performance of the ideal reactive controller in terms of its ability to suppress transient disturbances at levels of practical interest, is limited only by the control authority. The issues addressed in the current simulation work are therefore related to the assumption of ideal (infinite band width noise free) sensors and actuators.

4. Simulation shows no extreme motions of flexible elements when subject to the most severe shocks due to docking loads. The loads were modeled as impact forces at the docking interface. The max stress at the root of the array beam and astramast are at least a factor of 100 less than the proportional limit stress.

5. Gimbal rate response to the test impulse doublet was found to be as high as 6^o/sec for controller bandwidth of .05 Hz. Skylab class gyros are rate limited to $4\text{-}6^{o/sec}$. Therefore if bandwidth above .05 Hz is required for the class of space station studied here then three Skylab gyros is the minimum number to insure accuracy of 100-200 arc sec under the assumed level of transient loads.

2.5 CONCLUSIONS

The purpose of the study was to evaluate the basic stability and pointing performance of the core station when perturbed by impulsive disturbances that were intended to model torques produced during a productive work cycle. At the outset of the study, it was surmised that attitude stability might be jeopardized when the control band interacted with the flex modes. However, the theory shows that when the core station can be assumed rigid with respect to the control bandpass then the controlled response is asymptotically stable when the sensors and actuators are colocated anywhere on the core. A simulation of the flexible station and a control system consisting of multiple two axis double gimballed CMGs ideal attitude sensors was implemented. The attitude response of the system to impulsive disturbance verified the stability theory and showed substantial improvement in modal damping in most cases.

The conclusion of the study can be summarized as follows. Control of the free - free attitude modes using a regulator consisting of colocated CMG actuators and ideal rate and position sensors is asymptotically stable. However, the response of flex modes associated with the astromast is lightly damped with long settling time. If the resultant low-amplitude vibrations are objectionable, then flex mode damping must be introduced. Investigation of passive damping techniques should be a first priority. With these results, the important issues of core station free -free mode attitude control using a simple controller without additional stability augmentation of the flex modes has been addressed.

Alternate technologies for attitude control were intended to supplant the low-band controller in the event that attitude stability and performance were degraded. Analysis has demonstrated that the space station is attitude stable and performance is questionable only to the extent that low-amplitude vibrations of the structure are lightly damped. If the persistent low-amplitude, attitude oscillations are objectionable, then additional damping must be introduced. Investigation of passive damping schemes reveal that these techniques might be applied to the solar panel boom to dissipate the energy of the flex modes. Damping on the order of 10% has been demonstrated in laboratory experiments.

2.6 RECOMMENDATIONS

Continuing effort in attitude control for space station should concentrate on defining control requirements during buildup and construction phases including configuration with

the orbiter docked. Emphasis should be given to definition of control modes for each phase of evolution and schemes for managing the momentum envelope of candidate momentum transfer systems. Control modes would include electromagnetic sensing and actuation, momentum transfer, mass expulsion, attitude biasing, and appendage articulation.

During the configuration development phase of the previous study emphasis was given to achieving a dynamically balanced design. Mass balance will ensure that momentum transfer devices can be used for control without excessive propulsion requirements. All previous structural models will remain intact and no redesign of core station or appendages will be required to accommodate mass balancing. The space station configuration developed for this study will therefore be used without modification for evaluating candidate controllers for the proposed continuing effort. The simulation will be modified to include the control laws.

The output of the proposed study will be a control mode survey and trade off evaluation. Based on the results of the evaluation, recommendations will be made regarding the most effective attitude control strategy for space station during its evolution and long term operation. It is expected that the resultant control strategy will be synthesized from a set of technology elements already in place. The challenge will be to find new and creative applications for the basic elements with suitable modifications to the control laws that reflect modern computational techniques.

2.7 REFERENCES

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3.0 DATA MANAGEMENT

The data management section of this study was concerned with the data processing, storage and communications hardware and software that comprise the Space Station Data Management System (DMS). The study approach, analyses, and results are described in the following paragraphs.

3.1 INTRODUCTION

Data management includes the data system hardware and software needed to provide all Space Station data processing, storage and communications for onboard users, subsystems and payloads. This study was based on requirements determined in the previous study phase as shown in figure 3.1-1, and extended that work in three main areas. The first area is mission configuration analysis from a data management point of view; the second is the electronic hardware needed to provide data management services; and the third is the data management system software. These areas were addressed as three subtasks in this study.

Section 3.2 describes the study approach, followed by a technical discussion in section 3.3. The study results are summarized in section 3.4, and conclusions and recommendations are presented in sections 3.5 and 3.6 respectively.

3.2 APPROACH

Data management is an extremely broad study area because twenty or more Space Station subsystems, dozens of payloads and experiments, crew stations, computers, data storage devices, and communications transceivers are all interconnected through the data management network. The main function of data management is the integration of data from such equipment and subsystems to provide an effective, flexible, expandable and high performance transfer of information. The onboard system will be targeted toward a high degree of autonomy, but on the early space station, ground control, ground-based users, and other orbital platforms will also be connected through the DMS. The on board DMS, therefore, will be a cluster of computer-related equipment and software, within a much larger end-to-end data network. These considerations led to the conclusion that the DMS could be regarded primarily as a local area network (LAN). The

SUBSYSTEM	PROCESSING CHARACTERISTICS	STORAGE REQUIREMENTS	COMMUNICATIONS BANDWIDTH
CONTROL	FAULT TOLERANT COMPUTING SENSING, FILTERING ETC.	SMALL ARCHIVE SMALL BUFFERS	< 1 MBPS
COMMUNICATIONS	SWITCHING/MULTIPLEXING	LARGE BUFFERS	> 100 MBPS
DATA BASE	SEARCHING & SORTING	LARGE ARCHIVE	< 100 MBPS
DISPLAY	IMAGE GENERATION & SWITCHING	LARGE ARCHIVE LARGE BUFFERS	> 100 MBPS
MAINTENANCE	AUTO-TEST & SIMULATION	LARGE ARCHIVE	< 10 MBPS
MANIPULATOR	SENSING & MOTOR CONTROL	SMALL BUFFER	< 1 MBPS
SPACECRAFT TEST	SIMULATION & SWITCHING	LARGE ARCHIVE	> 100 MBPS
EXPERIMENT*	SENSING & SWITCHING	LARGE ARCHIVE LARGE BUFFERS	> 100 MBPS
AUDIO DISTRIBUTION	A/D & D/A CONVERSION	SMALL BUFFERS	< 10 MBPS
VIDEO DISTRIBUTION	ANALOG SWITCHING	NONE	> 100 MHz

*THEMATIC MAPPER, SYNTHETIC APERTURE RADAR ETC.
ARCHIVE: PERMANENT STORAGE FOR DATA RECORDING OR REFERENCE
BUFFER: HIGH SPEED TEMPORARY STORAGE

Figure 3.1-1 Data Processing, Storage and Communications Requirements

LAN concept, identified during the previous study, has been expanded here to include details of the LAN architecture.

The purpose of the mission configuration analysis subtask, which is the first subtask of the data management trade studies, was to assess the impact of candidate Space Station missions on the DMS and to ensure that the concepts developed in the previous study would meet requirements from those missions. This analysis was used to develop a model of the DMS for future simulation studies, and also provided an input to subtasks two and three. The network interface unit (NIU) and network operating system (NOS) were identified in the previous study and a cost-benefits analysis was conducted to determine their potential value to the program. It was estimated that a savings of $176M could potentially be realized if the LAN were developed, prior to space station development, and if the onboard subsystems and payloads of the station used the LAN hardware and software for data collection, processing, storage and communications. The higher cost alternative would have each experimenter develop his own DMS interfacing hardware and software, followed by a systems integration step to make the payload compatible with the onboard data management system. This approach results in needless duplication of effort, when compared to the LAN. Also, the savings of $176M refers only to development costs. It is believed that the LAN would also yield significant savings in operational costs, due to the ease of maintenance resulting from its standardized, modular organization and, due to the reduction in logistics requirements brought about by the use of a small set of common modules.

After completion of the mission configuration analyses, the impact on the DMS hardware and software systems could be assessed more readily. This permitted the primary hardware element of the DMS to be analyzed and described in greater detail, as subtask 2; with the primary software element defined functionally, as subtask 3. These elements are the "Network Interface Unit" (NIU) and "Network Operating System" (NOS), respectively.

The studies described above provided the basis for the identification of DMS technologies and task 2 of the study provided a cost and criticality analysis of the several technology items or areas identified. The approach taken in task 2 was to evaluate the role of each item or area from the perspective of the overall Space Station program. This involved estimates of relative need by the program, lead time, cost for development, and where possible, estimated value over the life of the Space Station. The most critical items are

those that are needed early in the program, that also have long lead times. This concept of need versus lead is explained more fully in section 3.4.

Task 3 was the preparation of technology advancement plans and the results of that task are reported in volume III.

3.3 TECHNICAL DISCUSSION

This section describes the technical content of the data management portion of the study. Because this was an extension of a previous study, some background material will be presented in each portion for clarity and continuity.

3.3.1 Mission Configuration Analysis

The identification of Space Station mission requirements on the DMS considered data communications bandwidths, data storage capacities, processing requirements, and interfacing requirements imposed by the experiments. Three example mission models were investigated, each having different data management requirements. These include Construction and Materials Processing Station (CAMPS), Communications and Data Management Station (CADMS), and Land, Ocean, and Atmospheric Research Station (LOARS).

CAMPS would be used for the construction of large space structures and spacecraft, plus production of semiconductors, alloys, and pharmaceuticals. Capabilities required in addition to a basic DMS functions might include data handling for teleoperators, robots, and a variety of remote sensors and effectors for construction purposes. The materials processing payloads would require automated process control capabilities, which would also require data management.

CADMS would provide command, control, and communications support for onboard and free-flying payloads and experiments. It would have powerful signal and data processing capabilities that could be shared by many experiments or spacecraft through a space-based communications network. It would use large high-speed data storage devices such as laser disks for archival storage of data generated and utilized on-orbit.

LOARS would be used primarily for remote sensing of weather, crops, sea state, and other planetary conditions and phenomena. It would carry high-resolution, high-bandwidth imaging sensors such as the Landsat-4 thematic mapper, and the Seasat synthetic aperture radar (SAR), but in more advanced versions. Such devices would place very high requirements on the data management system, providing a kind of worst-case DMS scenario. Therefore, LOARS was investigated in the greatest detail.

In the Advanced Platform Systems Technology Study (APSTS), a DMS configuration concept known as the fiber-optic backbone network was presented. This is a local area network suited for use aboard the Space Station because it is defined to have high reliability, maintainability and performance, while preserving an excellent potential for future expansion. This concept is defined to use digital baseband packet switching, as opposed to broadband or wavelength-division multiplexing. Broadband systems typically use a remodulator to establish connections between transmitters on one set of frequencies, and receivers on another. Broadband systems are vulnerable to single-point failures at the remodulator, and they require periodic adjustments to their analog and RF circuitry, making them unsatisfactory for use aboard the station. Wavelength division multiplexing systems typically require laser transmitters and optical multiplexers and demultiplexers. They have advantages over long fiber runs of a kilometer or more because many channels can be multiplexed onto a single fiber with considerable cost savings. But, over short distances such as aboard the station, the savings in optical fiber are insignificant and do not justify the expense and complexity of lasers and optical multiplexing equipment.

Figure 3.3-1 shows how the backbone network might fit into a space station configuration called the raft structure. The heavy lines are bundles of optical fibers, that interconnect the network interface units, or NIUs. The NIUs are modular electronic units, discussed in later sections, that house interface modules for the various digital and analog electronic devices carried aboard the station. Input data generated by these devices, such as high-bandwidth sensor data, are acquired by the NIU interface modules, stored temporarily, formatted, and routed to specific destinations by means of digital electronic communications or packet-switching. Specific destinations are addressable, depending on the application. Disk or tape storage devices, tracking and data relay satellite system (TDRSS) transmitters, and crew consoles are examples of output devices connected to NIUs.

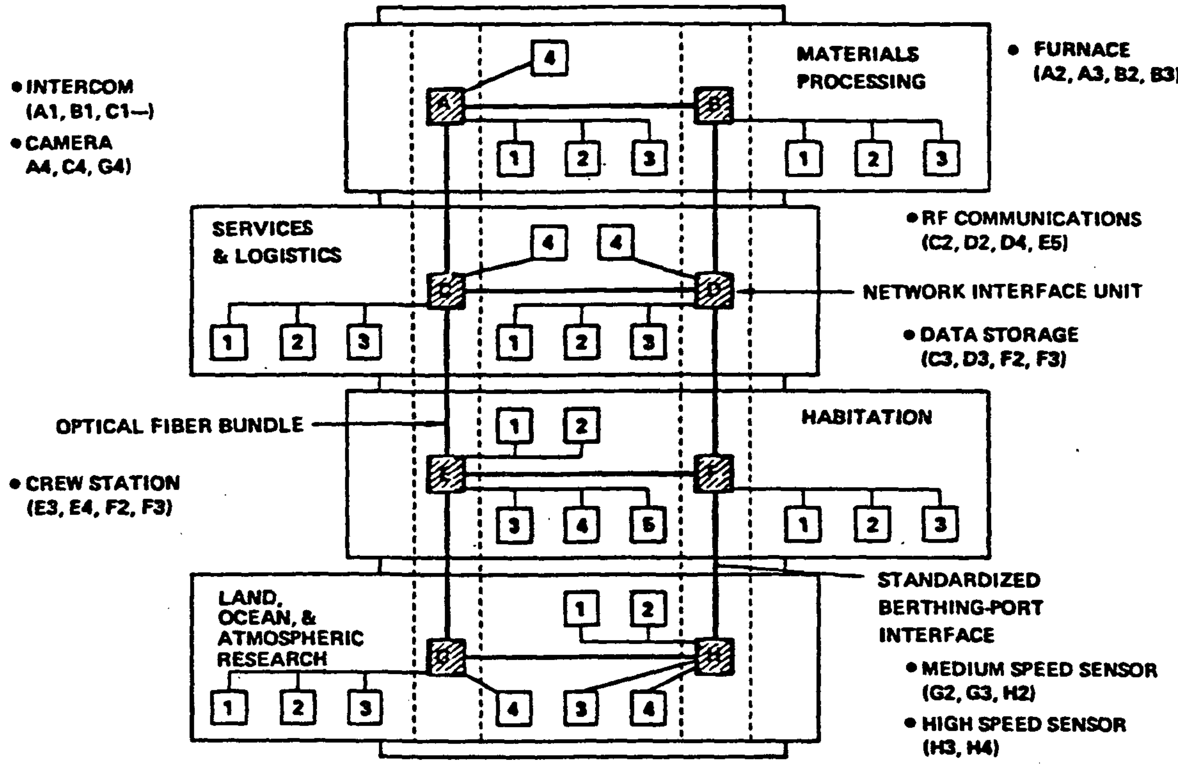


Figure 3.3-1 Fiber-Optic Backbone Network

The NIUs also support and control local data buses within each of the station modules. These buses could be standard serial buses such as the MIL-STD-1553B; however, present technology allows the use of higher speed buses, operating at 10-25 million bits per second (MBPS), such as the IEEE-802 proposed standard bus. Medium-speed devices, rather than high-speed sensors, would be connected to these buses. For example, small Winchester disk units typically operate at 10 MBPS, and several could be distributed about the station by connecting them to buses supported by different NIUs. This would provide a relatively low-cost, high-performance data base, that could be expanded almost at will by the addition of disk units.

This topology can be described as a two-level hierarchy. The NIUs and their interconnections provide for communications between station modules, and form the upper level of the hierarchy. The devices connected to the links and buses within the modules, supported by the NIUs, form the lower level. This approach allows for modularity at both levels. The NIUs handle inter-module communications through standard berthing-port interfaces, allowing station modules to be plugged-in at any berthing port. At the lower level, sensors and medium-speed devices can be plugged into the NIUs by means of standard interface cards and standard buses.

Multiple optical fibers are used for intermodule communications for several reasons. First, optical fibers have such a large potential bandwidth for existing and projected data communications applications that the same fiber bundles and connectors could be used throughout the lifetime of the station, although the NIU optical transmitters and receivers might be retrofitted at some future date. Second, the use of multiple communications channels provides for fault-tolerance, in the event of a hardware or software system failure. Third, optical fibers are nonconductive, and eliminate many potential problems with electromagnetic interference (EMI), ground loops, sneak circuits, or other undesirable electrical phenomena.

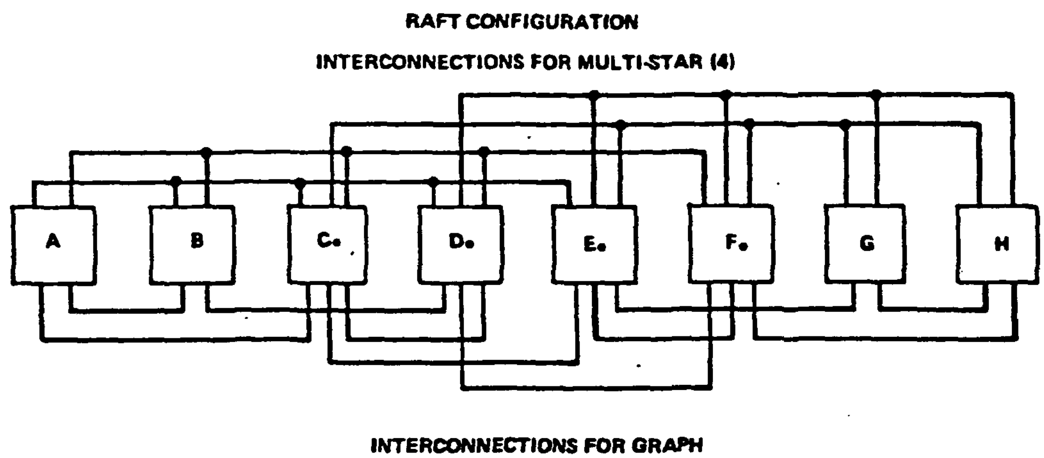
Fiber-optic technology is now mature enough to be used on board the station for most data communications applications, especially if light-emitting diodes (LEDs) are used as optical sources instead of laser diodes, and if PIN diodes are used as optical detectors. Laser diodes have a higher power output than LEDs, but they are not as readily available and have much shorter operating lifetimes. The lower output power of LEDs is not necessarily a problem if point-to-point communications links are used, or if the number of ports driven by the transmitter does not exceed a maximum of 20-30 in an optical

star-coupled configuration. Technical details on this topic are covered in the final report from the APSTS.

At least two fiber-optic backbone network topologies are viable for space station application and are shown in figure 3.3-2. The set of lines drawn above the boxes represents the interconnection topology formed by the use of four optical star couplers, located near NIUs C, D, E, and F. For example, the coupler located at NIU-C interconnects A through E, as shown by the lowest horizontal line. In this example, each of the couplers would interconnect a subset of five of the eight NIUs, so four five-port couplers would be required to assure a minimum of two redundant paths per NIU. The set of lines drawn below the boxes represents a point-to-point interconnection topology. Each link consists of a bidirectional channel, using two fibers with transmitters and receivers at opposite ends. Store-and-forward communications techniques are used, as opposed to the shared-bus techniques needed for the multi-star topology.

Data packets are multiplexed by means of time division multiple access (TDMA) techniques, so that multiple data streams can share each channel. This approach requires that a store-and-forward capability be provided at each NIU, so that packets can be received and retransmitted by intermediate NIUs in a series of hops to the final destination. This naturally provides for fault-tolerance because one or more alternate routes can be provided for use in case of a failure at one of the NIUs. Another advantage is the low optical power requirement for transmission across a point-to-point link. The transmitter must drive only a single optical fiber, with a single receiver. Therefore, both the optical source and the detector can be extremely small, simple, reliable, and low in cost.

The other viable fiber-optic topology uses multiple optical star couplers to interconnect the NIUs. It can be thought of as a multiple bus topology, with the star couplers providing the shared bus media; or, it can be regarded as an active-repeater system, with the NIUs functioning as the repeaters. From either viewpoint, the system is more complex than a simple passive star-coupled topology. The star couplers are each associated with an NIU, with several other NIUs attached at the ports. In this configuration, only a few ports would be needed at each coupler, perhaps five, so the optical power requirements would be quite low, allowing the use of LEDs as optical sources. This topology also provides fault-tolerance because each NIU has access to multiple star couplers, providing alternate communications paths in the event of a failure.



- BOTH TOPOLOGIES REQUIRE 20 OPTICAL TRANSCEIVERS
- BOTH NEED ROUTING AND RECONFIGURATION CAPABILITIES
- MULTI-STAR USES SHARED-BUS PROTOCOLS
- GRAPH USES TIME-DIVISION-MULTIPLE-ACCESS (TDMA)

Figure 3.3-2 Multi-Star Versus Graph Topologies

With either topology, a reconfiguration capability is needed in the NIUs so that alternate links or couplers can be selected in the event of a failure. In both cases, the NIUs must be able to store and forward messages or packets, because multiple couplers or links are provided, and the NIUs are not directly connected to each other by means of a single common bus. Both configurations can use LED sources, and PIN diode detectors. The transmitter and receiver logic needed is essentially the same in both cases, as shown in figures 3.3-3 and 3.3-4. These figures are block diagrams of the functions needed to implement optical transmitters and receivers, with the exception of the control logic. The transmitter converts digital data residing in memory to a serial bit-stream, encodes it with clock information, and uses the resulting signal to modulate an optical source. The receiver uses an optical detector to convert the signal back to an electrical form for decoding and conversion to a parallel word format that can be stored in a memory buffer. These examples use a 32-bit memory and a 100 MHz serial data rate, so the required memory cycle time (320 ns) would be relatively slow.

The two configurations use different access protocols for multiplexing the communications media. The graph topology uses simple TDMA, while the multiple-star topology may use polling, contention or token-passing. In a polling system, one of the NIUs functions as a controller, polling each of the other NIUs in sequence to enable them to transmit data on a given bus, one after the other. In a contention scheme, each NIU acts independently and "listens" for activity on the communications channel. If the channel is not busy, the NIU can transmit; however, two may transmit almost simultaneously, resulting in a collision. They must detect such bus contention, back off, and try again after a random delay interval. In a token-passing configuration, the system is initialized so that one of the NIUs "owns" a logical token that enables it to transmit a packet. After completing its transmission, it then sends the token to another NIU, which may transmit and then pass the token to the next NIU in sequence.

At this point, no clear reason exists for choosing either a pure graph or a pure multiple-star topology over the other. Communications network simulation studies are needed before a final configuration can be chosen. The next section describes the NIU concept in greater detail.

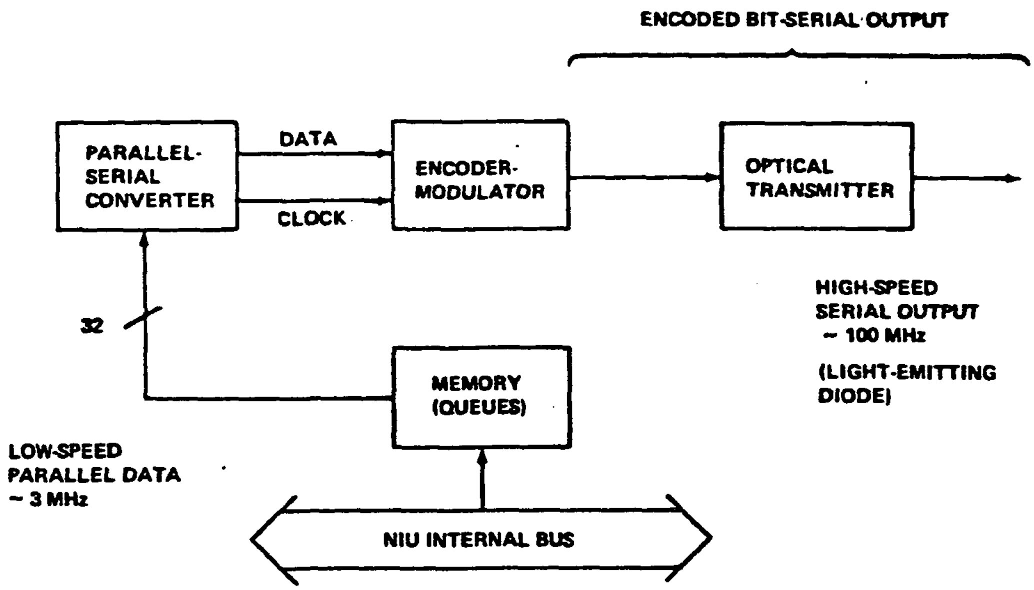


Figure 3.3-3 NIU: Transmitter Block Diagram

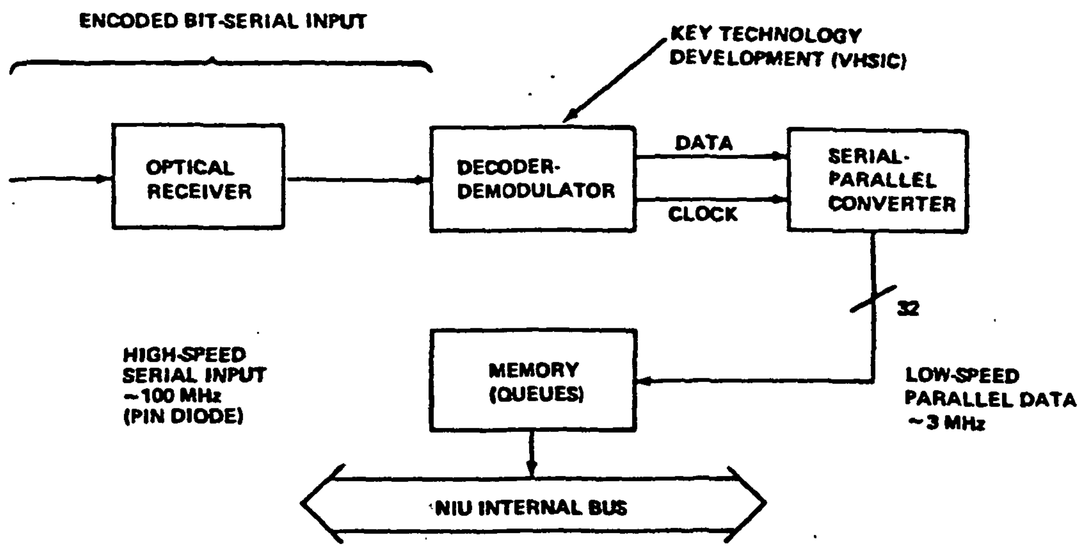


Figure 3.3-4 NIU: Receiver Block Diagram

3.3.2 Network Interface Unit Internal Organization

As shown in figure 3.3-5, the NIU is defined as a set of standard circuit cards that plug into a high-speed parallel data bus, housed in a rack-mountable chassis. The cards provide high-speed sensor control and data acquisition interfaces, instrumentation bus interfaces, fiber-optic intermodule communications transceivers, and many other types of input-output (I/O) interfaces and controllers. A set of standard modules can support a great many applications such as data acquisition through analog/digital converters, discrete I/O functions such as indicator lamp illumination or switch position-sensing and man-machine interfacing by means of keyboard and CRT controllers. Customized modules can also be added to the NIUs to support subsystems, payloads or specialized sensors.

A central processor unit (CPU) with associated memory is also shown in figure 3.3-5. Conceptually, this might be a high-performance 32-bit microprocessor if its only function is control of the NIU. However, multiple processors could also be installed in the NIU or connected to it through interfaces, to handle the onboard data processing tasks. Some of these could be specialized signal or image processors, or floating-point array processors, if they are required for onboard applications.

The main design conclusions reached as a result of this study are that the NIU should be modular, and should have a high performance potential. Space Station requirements will surely change over a period of many years. The basic NIU chassis and high-speed parallel bus can support such changes and upgrades if they are designed with flexibility in mind. The bus should have a 32-bit data path, with a minimum capability to transfer data words at a 16MHz rate. At 512 MBPS (32 * 16MHz) this bus has a bandwidth about five time greater than a super-minicomputer bus (e.g., VAX-11/780) of today. This is enough capacity to handle approximately 20 compressed digital TV channels, or thousands of digital voice channels. It is possible that future high-speed devices could generate data at higher rates, but such applications may be quite rare, and could be served by customized interface modules that handle data without involving the NIU bus.

Development of NIU modules would be a major project, because a dozen or more standard electronic interface modules would have to be specified, designed, and fabricated to meet most of the potential station applications such as data acquisition or subsystem interfacing.

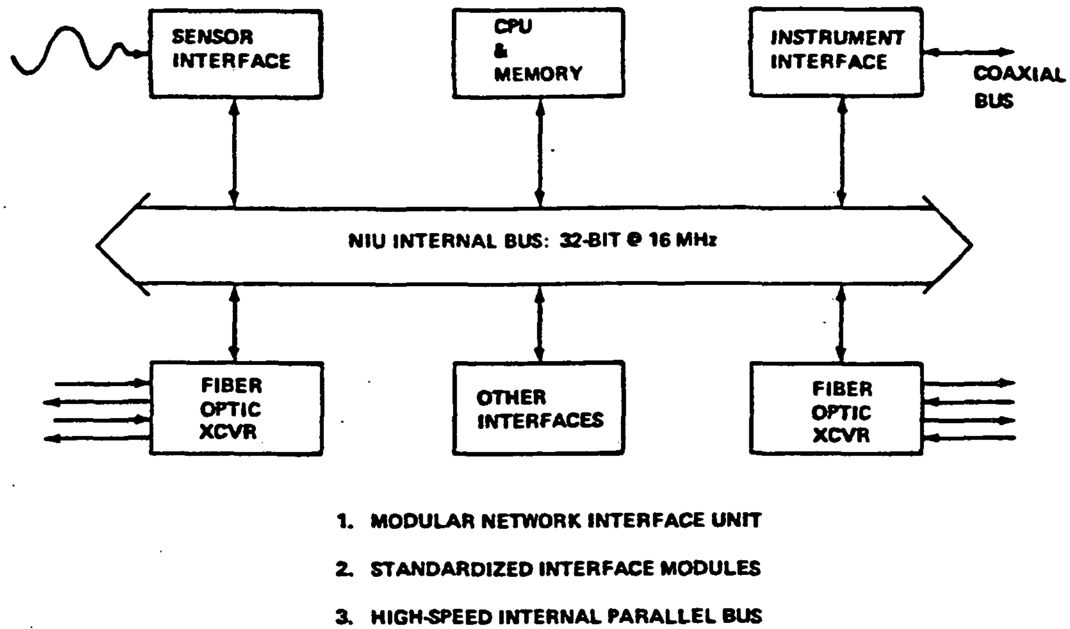


Figure 3.3-5 NIU: Internal Organization

Twelve such modules have been identified this far and they are listed as follows:

1. NIU control processor and cache memory.
2. Fiber-optic communications transceiver.
3. Instrumentation bus interface controller.
4. RF communications transceiver interface.
5. Digital voice communications interface.
6. Crew station console/CRT interface.
7. High-speed sensor data buffer.
8. Magnetic tape mass memory controller.
9. Magnetic disk mass memory controller.
10. Color video & graphics I/O controller.
11. Analog I/O interface.
12. Discrete digital parallel interface.

Figure 3.3-6 shows how typical DMS modules might be supported by the parallel and serial buses. High speed devices such as a CPU or a video interface would be installed in the NIU chassis and connected to the internal bus backplane or motherboard. Low and medium speed devices would be attached to the serial buses. Each NIU could be configured differently to support the equipment or applications within each station module; however, each would have a control processor and fiber-optic transceivers for network communications.

Other custom modules would also be needed for specialized applications such as high speed sensors. The software needed to provide DMS services (i.e., network operating system) would also require a major development effort, and should be done in conjunction with NIU development.

3.3.3 Network Operating System (NOS)

An operating system is the collection of software processes that control computer systems, as shown in figure 3.3-7. In a distributed system environment, or in a local area network, the term "network operating system" is frequently used, and has been adopted here. Aboard the Space Station, the NOS is conceived to have two major functions. First, it provides the operating environment for users of the DMS. Second, it manages

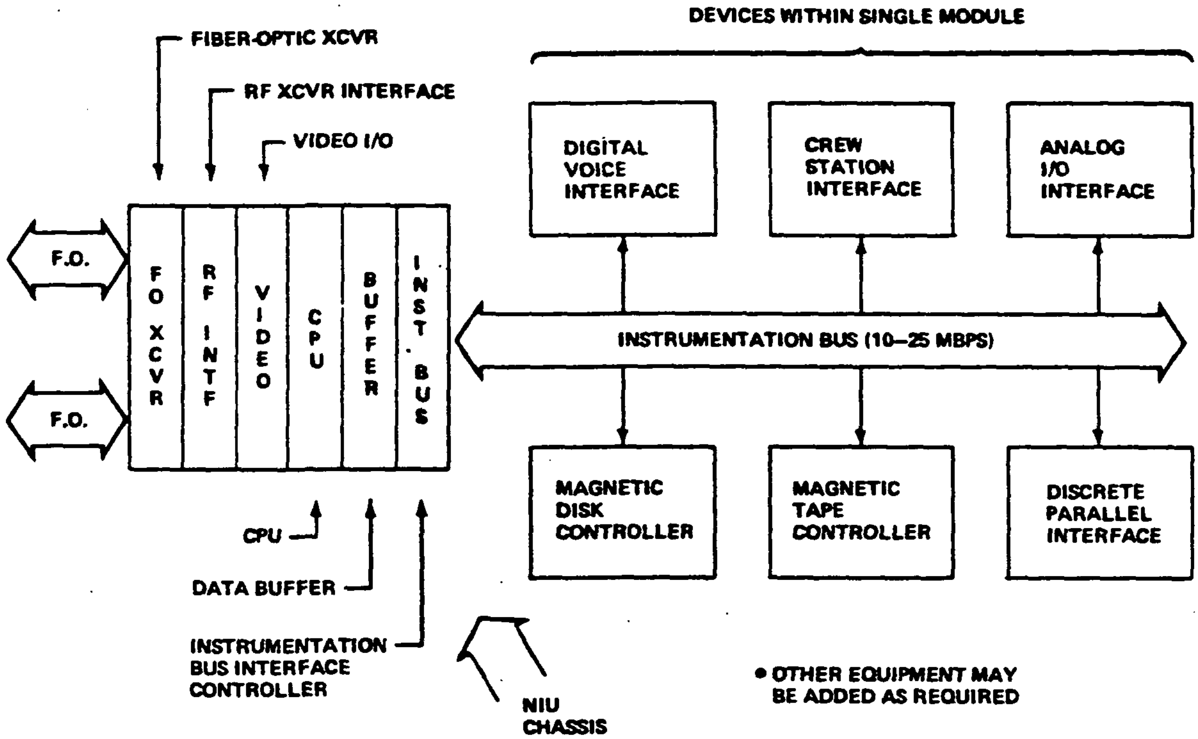


Figure 3.3-6 NIU Functional Partitioning

(EACH BOX REPRESENTS SOFTWARE RUNNING ON A SEPARATE PROCESSOR)

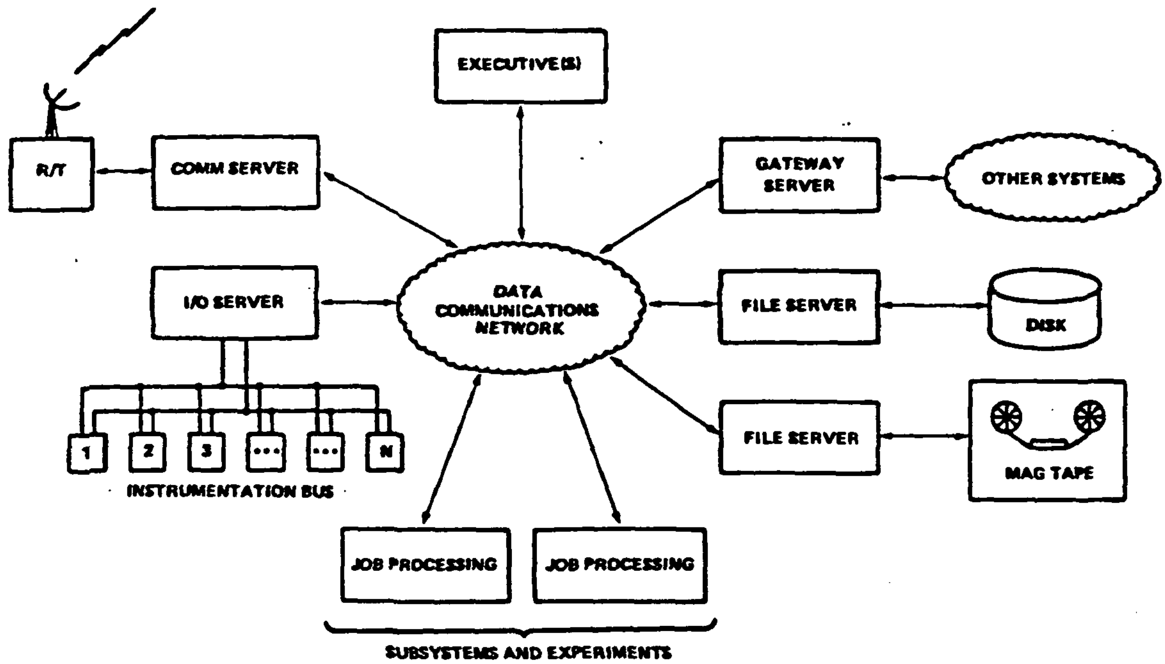


Figure 3.3-7 Network Operating System Example

the overall operation of the devices attached to the network, supporting status monitoring and control functions, and providing data storage, communications and processing services.

The NOS does not necessarily control the station systems or subsystems. Such functions depend on the NOS for computational support, and for control of interfaces, displays, keyboards and other devices that are used to operate the onboard systems. The actual control software for the various subsystems may be embedded in the devices, or may run on the applications processors provided by the DMS. Either way, the NOS is only indirectly involved in control of station subsystem application tasks. However, the NOS directly provides the user operating environment, as with any other kind of computer system. That is, in order to use the Space Station DMS resources, the crew, ground control engineers and operators, and remote scientific users will have to interact with the NOS. The user will enter commands by means of a console keyboard and display device, and will receive responses or status reports from the NOS by the same means. For example, commands would be entered to activate a synthetic aperture radar, steer its antenna to a given azimuth, acquire data for a given interval, process that data to generate high-resolution imagery, display the image on a video monitor, store it on a video disk, and downlink it to ground-based operators or investigators. Such a complicated sequence of operations could be initiated by a crew console command, or could be activated automatically by a command or signal from a ground control station. The NOS thus provides the capabilities that allow local or remote users to access payload data, initiate or schedule activities, run programs, monitor status, and to use the facilities provided by the DMS.

The NOS must also manage system functions within the DMS. This is a particularly important consideration for critical subsystems that utilize DMS processors, data base facilities, or communications links. For example, the health and status of the subsystems will be monitored by ground control, at least during the early stages of station operation. The data collected from onboard sensors such as temperature, pressure and attitude, will need to be formatted into messages and downlinked to ground sites. The processors and data communications interfaces and equipment needed are part of the DMS, and are controlled by the NOS.

Many such functions are critical, in that equipment failures could result in loss of automated control functions, or loss of ground control and communications. Computer and

electronic systems are subject to random failures, even though space-qualified devices may be utilized. For example, all known semiconductor devices are vulnerable to upsets or permanent damage from cosmic radiation, and computer memories are particularly sensitive. The only solution appears to be the provision of redundant equipment, with a capability for reconfiguration in the event of a failure.

Reconfiguration of a large distributed system or LAN can potentially be accomplished automatically, but the impact on system performance may be unpredictable. At a minimum, the basic operational capabilities of the system should be maintained, even though certain payloads or instruments might have to be shut down. Automatic fault detection within the DMS may be accomplished by use of built-in test (BIT) logic and software diagnostics. However, selection of alternate processors or communications paths, and shutdown of noncritical equipment should be a function of the NOS, under the control of one or more executive processes running on the DMS computers. Development of an automated diagnostic and reconfiguration software system, as part of the NOS, appears to be a major task. So-called nonstop computer systems exist, but they are not in common usage, and are not 100% effective. Considerably more research is needed if such a capability is to be available for use aboard the station. A key approach needed for such a technology development is the use of software simulation to model the DMS and the NOS, and to test the response of the system to the injection of simulated faults.

3.4 SUMMARY OF RESULTS

This section focuses on the specific technologies identified in the study, that are necessary or beneficial in the data management area. They are discussed above, but this section highlights the key areas, with some discussion of the technical merits of each item. The discussion is broken into two main segments. First, the results of the technical effort (task 1) are summarized. Second, the analyses of criticality, cost and program lead-time (task 2) will be discussed. This leads to the conclusion and recommendations in subsequent sections.

3.4.1 Task 1 Results

The technical effort was completed before the midterm review, and a total of sixteen candidate technology items were reported as worthy of development or extended study. The items were derived in part, by addressing the mission configuration analysis, the NIU

assessment, and the NOS subtask from three viewpoints: (1) what technologies are needed for DMS development; (2) what are those needed to provide a basic DMS operational capability; and (3) what are those needed to provide DMS support to missions such as LOARS, CAMPS, and CADMS. For example, items 2 and 13 below would be needed to develop the DMS, while items 1 and 5 would be needed to support the LOARS mission. The breakdown is representative of an advanced DMS; however, the use of modularity would allow the system to be gradually built-up to this level of capability, with mission-specific technologies incorporated last. The configuration analysis subtask led to the identification of eight items, as follows:

1. High-speed sensor data buffer.
2. Payload development system.
3. Maintenance expert system.
4. Space-qualified disk or bubble memory.
5. Onboard digital image processor.
6. Interactive crew workstation.
7. Adaptive digital control system.
8. DMS simulation software package.

The NIU description subtask resulted in the identification of five technology items or areas, as follows:

9. Decoder-demodulator integrated circuit.
10. Fiber-optic input/output interfaces.
11. Standard NIU data buses (internal and external).
12. Standardized microcomputer board set.
13. Interface verification test set.

The NOS definition subtask resulted in the identification of three software technology items for development, as follows:

14. Real-time NOS executives.
15. Layered communications protocols.
16. Distributed voting/diagnostic algorithm.

Task two resulted in some modifications to the priorities for each of the items or areas, based on program criticality, cost, and estimated lead time. These considerations are discussed in the next major section. The following paragraphs provide a brief description of the purpose or need for each item.

3.4.1.1 High-Speed Sensor Data Buffer

The high-speed sensor data buffer is needed for data acquisition from radars, CCD telescopes, and other sensors that will have their signal outputs digitized. The data buffer is a semiconductor memory that can be loaded with considerable amounts of data at very high speeds. The data can later be read out of the buffer and stored in an archival memory or transmitted to the ground, at a much lower speed, whenever convenient. For example, 800 dynamic memory ICs, with a one-megabit capacity each, would provide 100 million bytes of high-speed data storage. Such chips should be commercially available during the late 1980s.

3.4.1.2 Payload Development System

The payload development system would allow laboratories or contractors to develop flight hardware that is compatible with the onboard DMS, in a straightforward fashion. The development system would consist of a DMS compatible computer, a version of the NOS, and a NASA-approved high-order programming language package.

3.4.1.3 Maintenance Expert System

The maintenance expert system is a software package that would be used to aid crew members in on-orbit repairs or scheduled maintenance. It would have a graphics output capability for display of technical diagrams, and would also have a set of troubleshooting rules or techniques programmed in to aid the crew members in fault isolation. Software diagnostics and BIT circuitry could also be included.

3.4.1.4 Space-Qualified Disk or Bubble Memory

The space-qualified disk or bubble memory would provide online data storage for an onboard database. Currently, tape recorders are used in most space applications, but they provide very slow access to data, and are unsuitable for many database applications. Disks would provide the required speed, but reliability, rotational momentum, and uncertainties about head behavior in a microgravity environment might pose problems. Magnetic bubbles are a potential solution, but commercial availability may be low.

3.4.1.5 Onboard Digital Image Processor

An onboard digital image processor would have applications in the reduction or compression of data prior to storage or downlink. It could also be used in materials processing and life sciences laboratories for automated inspection of samples such as crystals or blood cells.

3.4.1.6 Interactive Crew Workstation

The interactive crew workstation would allow convenient access to the DMS database, and would provide a means for system command and control. It might include color graphics capability and could also allow access to the maintenance expert system. Multiple workstations would be located in various station modules.

3.4.1.7 Adaptive Digital Control System

An adaptive (or adaptable) digital control system would consist mainly of a set of standard software routines that could be used for different control system applications aboard the station. It would provide support for sensor data acquisition through use of control processes running on DMS computers. The control programs would also monitor the status of subsystems or equipment and would issue commands to drive relays, pumps, or other actuators and effectors. The approach would tend to reduce software development costs by providing a common library of functions that could be used in many control applications.

3.4.1.8 DMS Simulation Software Package

The DMS simulation software package is described in sections 3.5 and 3.6 and basically would allow detailed testing of the DMS network hardware and software before a commitment is made to a specific design approach. That is, software models of DMS devices, communications links and software processes could be evaluated or traded, before development.

3.4.1.9 Decoder-Demodulator Integrated Circuit

A decoder-demodulator integrated circuit would reduce the complexity of high-performance digital communications receivers, by replacing many discrete components in each receiver. This circuit is critical because it extracts data from an incoming modulated signal, and largely determines the achievable data rate (high) and error rate (low).

3.4.1.10 Fiber-Optic I/O Interfaces

The fiber-optic I/O interfaces are the transmitters and receivers used in the NIUs to establish high-bandwidth digital baseband communications throughout the station. They include buffer memories, modulators and demodulators, optical sources and detectors and control circuitry. These interfaces plug into the NIU high-speed parallel bus.

3.4.1.11 Standard NIU Data Buses

The standard NIU data buses are described in sections 3.3.1 and 3.3.2, and include the NIU internal high speed parallel bus, as well as the local serial buses within the station modules. The intermodule communications are handled by the fiber-optic I/O interfaces described above. The internal parallel bus connects standard CPU and interface boards within the NIU, as described in the next paragraph, while the local buses provide interfacing points for the medium-speed devices (10-25 MBPS) within each module.

3.4.1.12 Standardized Microcomputer Board Set

The standardized microcomputer board set could take two forms. Many system interfacing requirements could be satisfied by a set of common modules that plug into the NIUs. The other type would be used in payloads, instruments or other station equipment. The primary advantage in having a set of standard modules is the reduction in life cycle costs brought about by reduced logistics and maintenance difficulties. Customized circuit boards could be used where required, but duplication of functions would increase the number of spares that would have to be carried aboard the station and might cause supply problems over a period of many years.

3.4.1.13 Interface Verification Test Set

The interface verification test set would be used by station contractors to validate their equipment inhouse, before installation in the station modules. It would consist of standard interface connectors, circuitry and software, plus diagnostic software to exercise the various attached devices.

3.4.1.14 Real-Time NOS Executive

The real-time NOS executive consists of the software processes that control the DMS. Each computer in the system would have an executive process running continuously to schedule tasks, control attached devices, and handle communications.

3.4.1.15 Layered Communications Protocols

Layered communications protocols are the commonly accepted method for providing communications within a network. The lowest layers provide direct control of hardware. Successive layers are added to provide greater sophistication until the application layer is reached. The application layer gives users access to the network communications facilities.

3.4.1.16 Distributed Voting/Diagnostic Algorithm

The distributed voting/diagnostic algorithm would be used for automatic fault detection in the DMS. Box or module level redundancy would probably be used. For example, if box level redundancy is chosen for a functional area, critical processes would be executed on multiple processors with the results cross-checked by interprocessor communications. If at least three processors execute the same function and reach the same result, then the critical function can be initiated. If the results disagree, at least one of the processors must be in error and must be reset, tested, or shut down. Diagnostic routines could be run periodically, in the same way, to continuously test DMS health and status for either box level or module level redundancy.

3.4.2 Task 2 Results

In task 2 the goal was to evaluate each of the technology items or areas in terms of costs and benefits to the Space Station program. The specific approach taken in the DMS area was to estimate the time of need for the technologies, the required lead time, the development cost and risk, and the value or savings over the life of the station. Figure 3.4-1 summarizes the need, lead, cost, risk, and value for each technology, and the following paragraphs discuss the rationale for that data.

The 16 technology areas identified during task one were scored in five categories, with a rating of 0, 10, or 20. For example, a technology needed early in the program is more critical to success than one that is needed late, so a score of 20 would be assigned. The total scores give a rough estimate of the program criticality of each of the 16 technologies. That is, an area with a high score is an area that has a likelihood of greater program impact. An area with a low score, such as the high-speed sensor data buffer, may still be important; however, low cost and risk, combined with a late need and relatively short lead time mean that the relative program impact is quite low.

SCORING					
20	EARLY	LONG	HIGH	HIGH	HIGH
10	MID	MID	MID	MID	MID
0	LATE	SHORT	LOW	LOW	LOW

TECHNOLOGY AREA	NEED	LEAD	COST	RISK	VALUE	TOTAL
HARDWARE						
●STANDARD CARDS	20	10	20	10	20	80
●STANDARD BUSES	20	20	10	0	20	70
●F.O. TRANSCEIVERS	10	10	10	10	10	50
●DECODER CHIP	10	10	10	10	10	50
SOFTWARE						
●SIMULATOR	20	10	10	20	20	80
●EXECUTIVES	20	10	20	10	20	80
●PROTOCOLS	20	10	10	10	20	70
●DIAGNOSTICS	10	0	0	0	10	20
GENERAL SYSTEMS						
●PAYLOAD DEV. SYS.	20	20	10	10	20	80
●MAINTENANCE EXP.	10	10	10	20	20	70
●IMAGE PROCESSOR	0	20	20	20	10	70
●CONTROL SOFTWARE	10	10	10	10	10	50
●INTERFACE TEST SET	20	10	10	0	10	50
●CREW WORKSTATION	10	0	0	0	10	20
●DISK/BUBBLE MEM.	10	0	0	0	10	20
●DATA BUFFER	0	0	0	0	10	10

Figure 3.4-1 Criticality of Technologies

3.4.2.1 High-Speed Sensor Data Buffer

The high-speed sensor data buffer will be needed after the station becomes operational to support imaging sensor payloads. It seems to pose no great difficulties in terms of lead time, cost, or risk, except for the possibility of data disruption by cosmic radiation. This type of sensor data is not flight critical, and the upset problem should be manageable if error detecting and correcting codes are used to preserve data integrity. The primary savings will be in the elimination of high-speed onboard recorders, and the related maintenance and replacement costs because semiconductor memories are very reliable compared to electromechanical devices.

3.4.2.2 Payload Development System

The payload development system is, by definition, required for development of payloads for various onboard applications and is therefore an early-need item. Choice of a processor, language, and a set of I/O interfaces for a wide variety of applications are the greatest difficulties. The main value is commonality and standardization, with savings in development cost due to reduction of duplicated effort at different facilities.

3.4.2.3 Maintenance Expert System

A maintenance expert system would be very useful to crew members in troubleshooting and scheduled maintenance. However, this is an emerging technology that will need considerable amounts of time and money for development. The value would be high because it could save one-half of a crew member's time, or more, but it is also a high-risk development item.

3.4.2.4 Space-Qualified Disk or Bubble Memory

This memory would support an onboard database, and would be used primarily for station operations, rather than for experiment data storage. The disk would be a development from existing technology and would involve high risk only if its rotational momentum caused unacceptable torques, or if the microgravity environment resulted in unpredictable read/write head behavior. A magnetic bubble memory is a viable alternative, that involves no moving parts. It would not have mechanical problems and should be very reliable, but availability of space qualified bubble memory chips is in doubt. Therefore, this technology involves some risk, but seems essential for normal station operations.

3.4.2.5 Onboard Digital Image Processor

An onboard digital image processor would be an advancement from current technology. Such specialized processors are in use in medical imaging laboratories and at NASA facilities. With new (VHSIC/VLSI) technology, it should be possible to package and qualify such a processor for the station, but it would probably be quite expensive to develop because a considerable amount of software is also needed. The main value would be a reduction in the need for high-bandwidth imagery transmission to and from ground-based facilities because digital imagery could be enhanced or otherwise processed onboard.

3.4.2.6 Interactive Crew Workstation

An interactive crew workstation would be an advanced data entry and display console utilizing advanced microelectronics and software. Examples of advanced technologies are flat panel displays, high-resolution color graphics, multifunction keyboards, and expert systems. The workstation would be needed for normal operations and would have a high value because of potential increases in crew productivity. The risk would be relatively low if this is viewed as an evolutionary development. That is, only the essential capabilities would be implemented early in the program, with enhancements added later.

3.4.2.7 Adaptive Digital Control System

This technology would be needed for development of onboard control systems early in the program. That is, if a common library of control system software is to be of use, it will have to be available when the systems are implemented and tested. The risk is probably less than the risk of developing and integrating ten or more separate and independent control software packages, and the same rationale appears to apply in terms of life cycle cost reduction. Therefore, the value could be quite high.

3.4.2.8 DMS Simulation Software Package

If a simulation package is to be utilized in the early stages of DMS design, it will obviously have to be developed very soon. It could be used later in the program to help determine the impact of system modifications, but its primary value is in the early analysis and trade study phases when different system concepts must be evaluated. The DMS simulation software package has the highest priority of any of the technologies addressed in this study. The main risk is that the simulation runs might have poor

verisimilitude, that is, if a true representation of the DMS is not modeled accurately, the simulations may be useless or detrimental to station development.

3.4.2.9 Decoder-Demodulator Integrated Circuit

This IC would be needed when the station becomes operational, but discrete logic circuits could be used to support DMS development. It would not be a tremendously complicated circuit because it would consist primarily of a phase-locked loop and a few shift registers. However, it might be difficult to achieve high data rates with current technology. The primary value would be a reduction in the complexity of onboard digital communications receivers, including those used for intermodule optical communications links.

3.4.2.10 Fiber-Optic Input/Output Interfaces

As with the decoder-demodulator IC, the optical I/O interfaces would be needed at the IOC point, but the remainder of the DMS could be developed using alternate means of digital communications. The space-qualified interfaces could be substituted before the station enters its operational phase. The main risk seems to be the potentially low reliability of the optical sources and detectors, and the fragility of the optical connectors. The primary values appear to be high bandwidth potential for video and high-speed sensor data distribution, and electrical isolation between equipment located in different space station modules.

3.4.2.11 Standard NIU Data Buses (Internal and External)

The primary advantages of bus standardization appear to be ease of systems integration, and reduced development and life-cycle costs due to equipment commonality. The NIU internal parallel bus, and the intra-space-station module serial buses will be needed during system development. They are an advancement from current technology, and seem to pose no great risks. However, once specified, they will probably have to serve as standards throughout the life of the station. Therefore, they should be evaluated and specified very carefully, to ensure that sufficient performance and growth potential are provided to serve station requirements over many years. The DMS simulation software package should be of considerable value in this analysis and specification process.

3.4.2.12 Standardized Microcomputer Board Set

A standardized set of circuit boards could be developed relatively easily, and would be of considerable use in various subsystems, instruments, and experiments. Most such appli-

cations will require a small amount of data processing capability for status monitoring, control, or data collection; and microcomputer technology is well suited for these roles. If standard boards are to be used, then early development is essential. The main values are reduced development and life-cycle costs, due to a reduction in duplicated hardware, reduced software development costs, and limitations in the variety of spares that must be procured and carried onboard the station. Early obsolescence is a potential disadvantage; however, if the boards are configured for a standard parallel bus, such as the NIU internal bus, then new versions can be introduced as technology developments warrant.

3.4.2.13 Interface Verification Test Set

An interface verification test set would be required early in the development program, to ensure that different contractors conform to DMS interfacing standards and communications protocols. Lead time may be a problem because the standards and protocols must be developed first. Development of the test set should be relatively straightforward from that point, especially if the standard board set can be utilized. The primary value is ease of systems integration over the life of the station.

3.4.2.14 Real-Time NOS Executive

The NOS executive modules provide all DMS control and operational functions and are needed early in the program to allow integration of equipment into the DMS. This area involves the greatest potential risk and cost in the software area because flight critical functions may be involved, as well as all DMS-user support capabilities. Efficiency, high performance and fault tolerance are crucial to program success.

3.4.2.15 Layered Communications Protocols

The DMS cannot function without communication protocols. They are needed for early systems integration and should remain constant over the life of the space station. Such protocols have been in use for several years (e.g., ARPANET) and do not require technological breakthroughs for implementation. However, specification of the protocols will have significant implications in terms of reliability and efficiency of onboard and external communications. The protocols must be carefully analyzed and specified; this process will almost certainly require the DMS simulation package described above.

3.4.2.16 Distributed Voting/Diagnostic Algorithm

If the DMS is to have a fail-safe, fail-operational capability, then some means of automatic fault detection is clearly required, at least for critical functions. An algorithm

that uses multiple distributed modules or boxes to cross-check computational results is needed by the time the station enters its operational phase. The primary risk is that the algorithm may cause a considerable amount of processing overhead, or that it may operate unreliability. Its value is in the reduction of risk with respect to crew safety and mission success.

3.5 CONCLUSIONS

The work performed during this study led to conclusions in three main areas, involving data management system configurations, system hardware (NIU) and system software (NOS). Three potential mission configurations were analyzed, with the Land, Ocean, and Atmospheric Research Station (LOARS) model developed in enough detail for simulation studies to commence. The NIU was analyzed to the point where component technologies could be identified; and the NOS was defined to a level of detail that included identification of software functions and their functional interrelationships. These analyses were then used in the second part of the study, task 2, to help in the evaluation of the need for each technology in terms of program phase, plus estimates of relative cost, risk and value to the program. This work is summarized in figure 3.4-1.

In the previous study, development of the NIU was estimated to cost $9.4M and the NOS development was estimated to cost $6.0M. The RCA PRICE computer model was used for these estimates, as described in volumes II and IV of the Advanced Platform Systems Technology Study. During the present study, a third estimate derived from in-house experience was made for development and use of a DMS software simulation package. Over a six-year period, leading to space-qualified hardware and software, development and use of the simulator is estimated at $6.85M, as described in volume III of this report: "Technology Advancement Program Plan."

Incorporation of the simulator, the NIU and the NOS recommendations provide the greatest cost savings to the program. The total cost of development for the three items is $22.25M over six years. With estimated development cost savings to the program of $176M, primarily in reduced systems integration costs, the ratio of benefits (savings) to cost is 7.9. That is, for every dollar spent on network simulation, hardware (NIU) and software (NOS), NASA can expect savings in DMS development cost of almost eight dollars. The potential savings in operating costs are also considered to be quite significant, and are worth investigating in future studies. Space Station DMS development

involves critical paths. That is, some technologies are needed before others, and are in fact needed to facilitate their development. The most critical technology area appears to be computer-aided engineering (CAE), or computer simulation of networks and complex data systems.

Simulation is an essential analysis tool for DMS development. If an adequate simulation capability is available, then logical models of system components can be developed and evaluated in different configurations with optimization as the primary goal. The station has many potential missions and operational requirements that must be fully evaluated before advanced development can begin. Hence, a DMS simulation system is the most valuable analysis tool that could be used in preliminary configuration studies.

After the optimum system architecture has been defined, implementation can begin. This will likely involve development of engineering models first, with flight hardware to follow. This will require standardization of system hardware and software interfaces and communications protocols to facilitate systems integration. DMS system components and functions will be under the control of software executives that reside on DMS computers. Therefore, the processors, interfaces, buses, protocols, and executives will have to be specified and developed very early in the program, after simulation studies. Then, development of applications, payloads, experiments and subsystems can begin, insofar as the DMS is involved. That is, those areas that require DMS services can be developed independently up to a point until they reach the place on their critical paths where the DMS services are absolutely necessary. At that time, the DMS must be up and running, at least in a preliminary form, or Space Station developmental progress will be hampered at best, or halted at worst.

3.6 RECOMMENDATIONS

As a result of this study, it is recommended that DMS simulation capabilities be developed first, so that potential mission configurations and the interactions between DMS hardware and software components can be fully analyzed in time to support space station full-scale development.

The other technologies needed for DMS development have almost as high a priority as the simulator. Two such items were identified during this study, as follows:

a. Interface verification test set.
b. Payload development system.

The test set would be of great benefit to contractors, and the development system would be useful to experimenters or entrepreneurs who wish to develop DMS-compatible payloads. Of the remainder of the sixteen technology items, none could be eliminated as a result of this study. They are all needed to enter the space station full-scale development phase, but are of a less urgent nature. Simulation is the most urgent technology item, and because of its early use in space station development, it is discussed in more detail with second tier recommendations.

Simulation of large data systems is a computer-aided engineering (CAE) technique that can greatly reduce development costs, while increasing system effectiveness. Almost by definition, large systems and networks are extremely complicated and are usually quite costly. Before committing large sums to the design of such a system, a model should be developed using simulation software package to give an early indication of system behavior in realistic scenarios and to allow a degree of optimization prior to actual development.

Selection of the final DMS architecture from the results of this study would be premature but progress has been made in the development of tools to support that decision. Also, of the three mission models considered in the first part of the study, the Land, Ocean, and Atmospheric Research Station (LOARS) model has been developed in enough detail to allow initial modeling and simulation activities to begin as an internal R&D project supported by BAC.

As mentioned above, one of the purposes of this effort is to determine how fault-tolerance can be implemented in the DMS. Figure 3.6-1 shows how the simulation could be used to inject errors and hard faults into the model, to determine the impact on system functionality, and to test the performance of automatic reconfiguration algorithms. The simulation consists of several software modules, as shown in the diagram. The most important are the packet producers, servers, consumers, and the instrumentation module. Producers simulate the production of messages or packets that, in a real system, would be transmitted by the devices that make up the DMS. The servers simulate the behavior of the network communications components and software protocols. Consumers are the

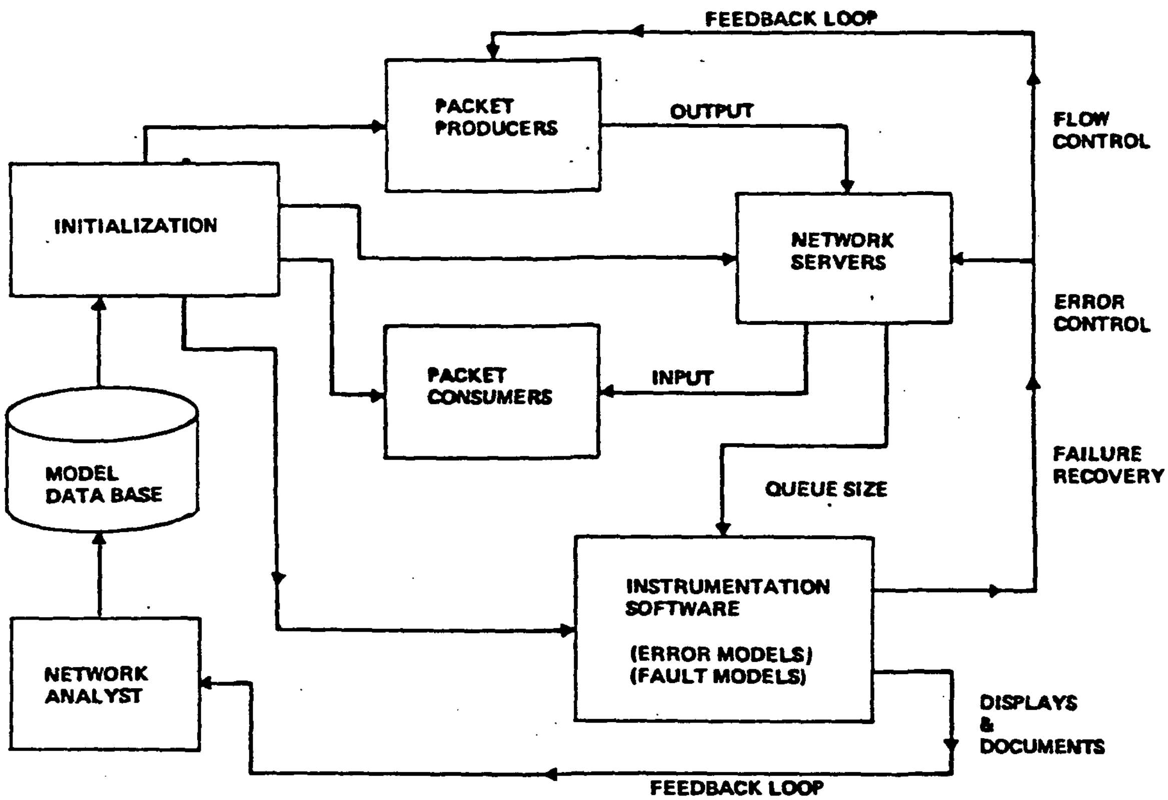


Figure 3.6-1 DMS Closed Loop Simulation

devices to which the messages or packets are sent. And finally, the instrumentation module performs data collection and simulated fault injection.

When fully devloped, the simulation package would allow the user to design a network interactively, using a color graphics terminal. Models of the devices attached to the network are entered into the system database, and graphical representations will be displayed on the color monitor, including the network interconnections. The simulation output consists of statistical measurements acquired by the instrumentation module, displayed graphically as letters, numbers and colors. For example, the symbol for a failed device could be displayed in red, and the utilization of a communications link displayed as a numerical percentage.

Simulation allows the use of modern CAE techniques in DMS design, in the same way that integrated circuits are designed and simulated prior to fabrication, and for the same reasons. Simulation can give an excellent indication of system performance before major resources are committed to production and various concepts can be traded and compared to produce an optimal design.

4.0 LONG-LIFE THERMAL MANAGEMENT

4.1 INTRODUCTION

The objective of the present long-life thermal management study was to identify heat transport system technologies that increase performance, enhance system life, and reduce system weight and cost. Emphasis was placed on two-phase heat transport systems that may offer significant performance benefits. These systems absorb and reject heat at a near constant temperature. This isothermal characteristic simplifies thermal interfaces and allows heat loads to be placed at any available location thereby providing a high degree of flexibility in reconfiguring the space station. Reduced pump power requirements and heat transport by latent heat of vaporization provide size and weight reductions compared to a conventional pumped liquid-loop heat transport system. These comparisons made possible the identification of new technology areas requiring advancement.

The two technology areas identified were—

1. Two-phase water thermal transport loops for inhabited environments.
2. Pumps and heat exchangers for liquids in the nearly-saturated state in zero gravity.

The study approach, technical discussion of study, results, conclusions, and recommendations are presented in the following sections.

4.2 APPROACH

The overall study was divided into three tasks outlined below:

Task 1

1. Define baseline pumped two-phase heat transport system.
2. Optimize baseline system.
3. Identify optional systems.
    a. Pumped liquid loop.
    b. Capillary two-phase.
    c. Alternate two-phase pumping concepts.

Task 2

1. Compare baseline and optional systems.
2. Select technologies for advancement.

Task 3

1. Develop technology implementation plan.

This section of the report describes the task 1 and task 2 efforts.

The study groundrules are described in section 4.3.1, and the basic heat transport systems are defined in section 4.3.2. The detailed technical discussion for system optimization and comparison is covered in sections 4.3.3-4.3.8. The summary of results, conclusion, and recommendations are presented in sections 4.4, 4.5, and 4.6, respectively.

Detailed analyses were performed for pumped two-phase, capillary two-phase, and pumped liquid-loop systems. These systems share common elements (pipes, radiators, heat exchangers) and each must be optimized to provide a valid comparison. Consequently, the technical discussion is based primarily on system elements rather than on a task 1 and task 2 division.

4.3 TECHNICAL DISCUSSION

4.3.1 Groundrules for Study

The following basic groundrules were established for the study:

1. Platform total heat load: 25-150 kW.
2. Transport distance: approximately 150 ft one way.
3. Grumman Space Constructable Radiator 1.2 lb/ft^2.
4. Power penalty: 350 lb/kW.
5. Heat transport fluids:
    a. Two-phase: ammonia.
    b. Pumped liquid: Freon 11, Freon 114, ammonia.
6. Low temperature (about 40^oF) heat rejection for metabolic and battery heat loads.
7. High temperature (about 80^oF) heat rejection for remaining loads.
8. Radiation sink temperature: 415^oR.

9. Pumped water heat transport loop inside pressurized modules.
10. Elements for each system:
    a. Radiator.
    b. Cold plates.
    c. Pressurized module interfaces.
    d. Transport loop.
11. Thermal storage interface inclusion is beyond scope of study.

During the course of the study results showed that there were only minor differences between Freon 11 and Freon 114. Consequently, the detailed analyses were completed for Freon 11 only. It also became apparent that a two-phase water heat transport system inside the pressurized modules offered benefits and was added to the study.

The groundrules listed here were augmented by a baseline space station definition (sec. 4.3.7.1). This further definition was required for the heat transport system comparison on an overall system basis.

4.3.2 Heat Transport Systems

Figure 4.3-1 shows the basic heat transport systems that were analyzed in this study. The baseline is a pumped two-phase system with a liquid and vapor lines. A mechanical pump is used to pump the liquid condensate from the radiator to the heat source heat exchangers (evaporators). Control valverizing a two-phase heat transport systems within the long life requirement constraints. Each of these approaches produced useful advancements in the understanding of technology issues and development needs.

The overall study was divided into four tasks. During task 1 the design concepts required in each of the four study areas were refined and comparative studies were conducted. The pumped liquid loop is similar to the baseline system except that the heat is transported as sensible heat rather than as latent heat of vaporization.

Alternate pumping concepts were briefly considered for the baseline pumped two-phase system. One concept would use an osmotic pump in the liquid line. The liquid would consist of a solvent and solution separated by a semipermeable membrane. The osmotic

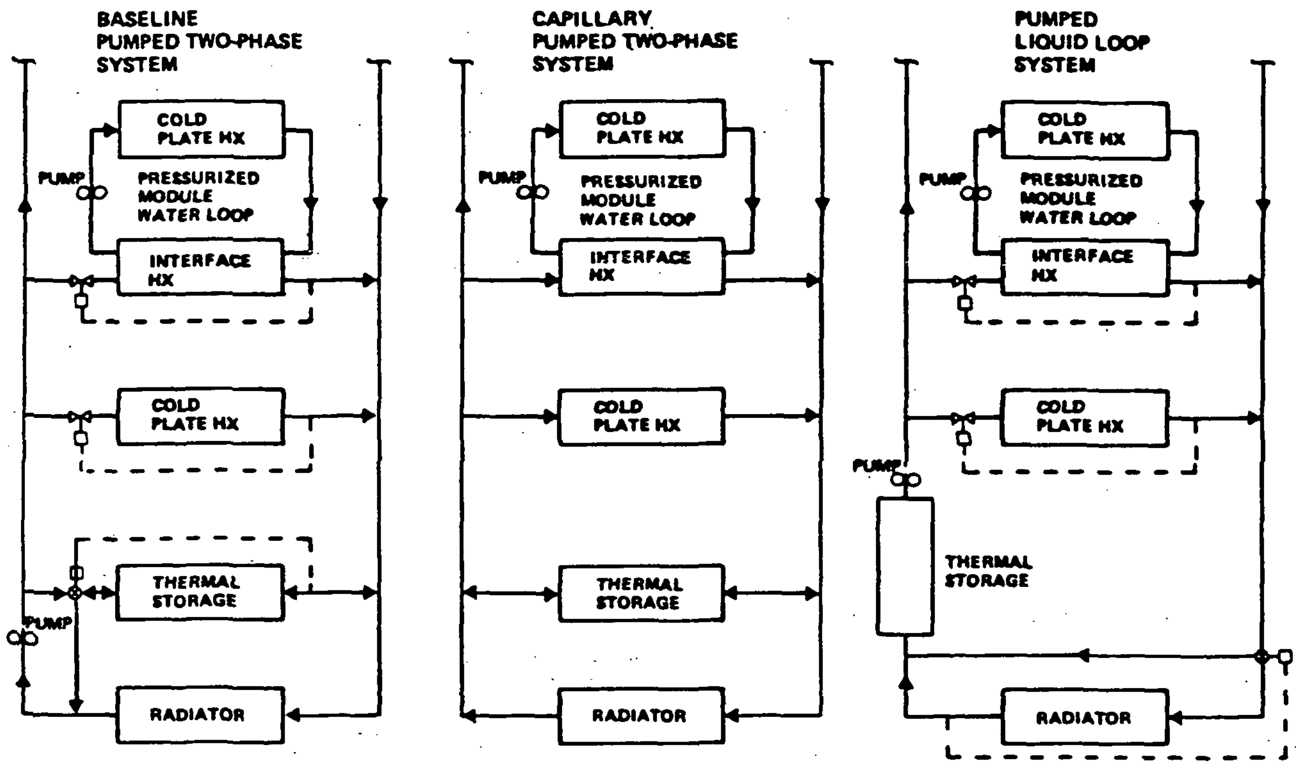


Figure 4.3-1 Heat Transport Systems

pressure across this membrane causes solvent flow through the membrane into the solution. The solvent evaporates from the solution at the evaporators, condenses in the radiator, and returns to the membrane. The other concept considered uses an ion drag pump. This pump uses a high voltage probe to generate and accelerate ions in the fluid. These ions exchange momentum with the fluid and produce the pumping action.

4.3.3 Heat Transport Loop Sizing

4.3.3.1 Pumped Two-Phase Transport Loop

The pumped two-phase loop consists of a pumped liquid supply line to the evaporators and a vapor return line to the radiator. The weight of the loop includes line weight, fluid weight, and pump power penalty. For turbulent flow (cases of interest are in turbulent flow regime) and small wall thickness compared to line diameter, the weight per unit length of line (vapor or liquid) is given by

$$Wt/l = \pi \rho_o tD + \frac{\pi}{4} \rho D^2 + F \left(\frac{\gamma}{\eta}\right) \left(\frac{\mu^{0.25}}{\rho^2 h_{fg}^{2.75}}\right) \frac{Q^{2.75}}{D^{4.75}}$$

ρ_o = density of line material (aluminum in present study)
t = wall thickness
D = inside diameter
ρ = fluid density
μ = fluid viscosity
h_{fg} = latent heat of vaporization
Q = heat load
η = power penalty
γ = pump efficiency

The factor F includes a factor to account for additional pressure losses due bends, valves, etc. (assumed to be 25% in this study) and a factor to account for the load distribution along the line. Two load distribution cases were considered. The most severe case is that of the load being concentrated at the opposite end of the loop from the radiator. In this case F = 1.25. The other case is that of a uniform load distribution along the loop where F = 1.25/2.75.

The assumed minimum wall thickness is 0.03 inches and is increased as necessary to keep the wall stress below 5000 psi (based on fluid vapor pressure at 125°F). For the increased wall thickness cases, t is proportional to D and an analytical expression can be found for the optimum diameter that minimized the weight per unit length. Otherwise, the optimum diameter must be determined iteratively.

Two-phase ammonia heat transport loops were optimally sized as a function of heat load for high (86°F) and low (32°F) temperature systems. The line sizing, pressure drop and pumping power, and weight per unit length are shown in figures 4.3-2, 4.3-3, and 4.3-4, respectively.

For the pumped two-phase transport loop the optimization is essentially independent of other system component (e.g., radiator) optimizations. The vapor line pressure drop will provide a coupling of the transport loop optimization to other system component optimizations since this gives rise to a difference in evaporation and condensation temperatures (i.e., an additional temperature drop between heat source and radiator). This temperature difference, however, is insignificant for the two-phase ammonia systems considered in this study.

4.3.3.2 Capillary Two-Phase Transport Loop

The capillary two-phase loop is similar to the pumped two-phase system except that the pumping action is provided by surface tension. The loop weight consists only of line and fluid weight. The weight per unit length (of total transport distance) is

$$Wt/l = \frac{\pi}{2}\rho_o \left[(tD)_v + (tD)_l\right] + \frac{\pi}{8}\left[(\rho D^2)_v + (\rho D^2)_l\right]$$

where subscript v refers to vapor and l refers to liquid.

The vapor and liquid line sizes are constrained by the surface tension pumping capacity per total (previously, a detailed analyses of the thermal storage interface was beyond the scope of the study.)

The capillary two-phase system is similar to the baseline system, except pumps and valves are not required. The capillary wicks in the heat exchangers provide the required transport length.

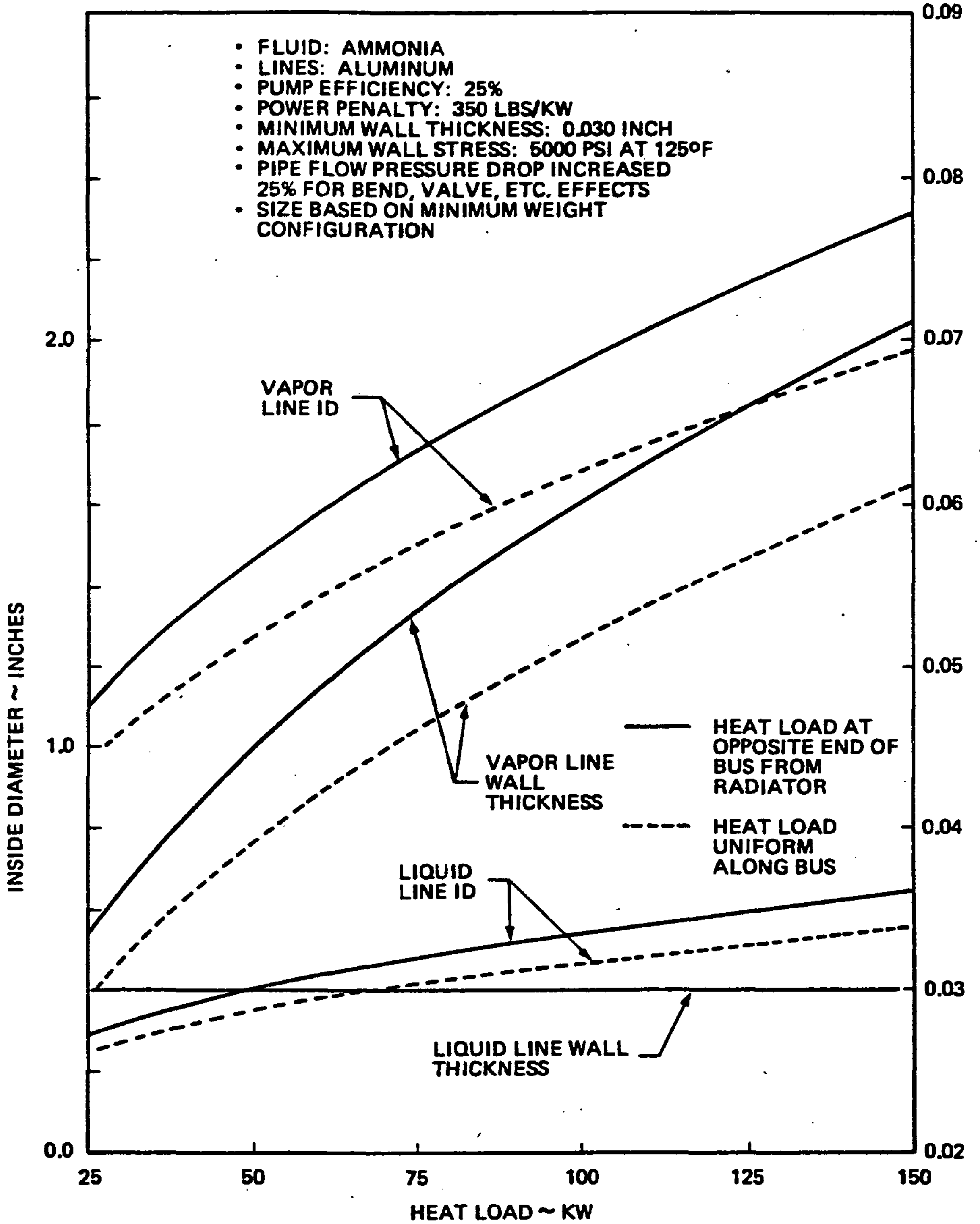


Figure 4.3-2 Pumped Two-Phase Bus Sizing

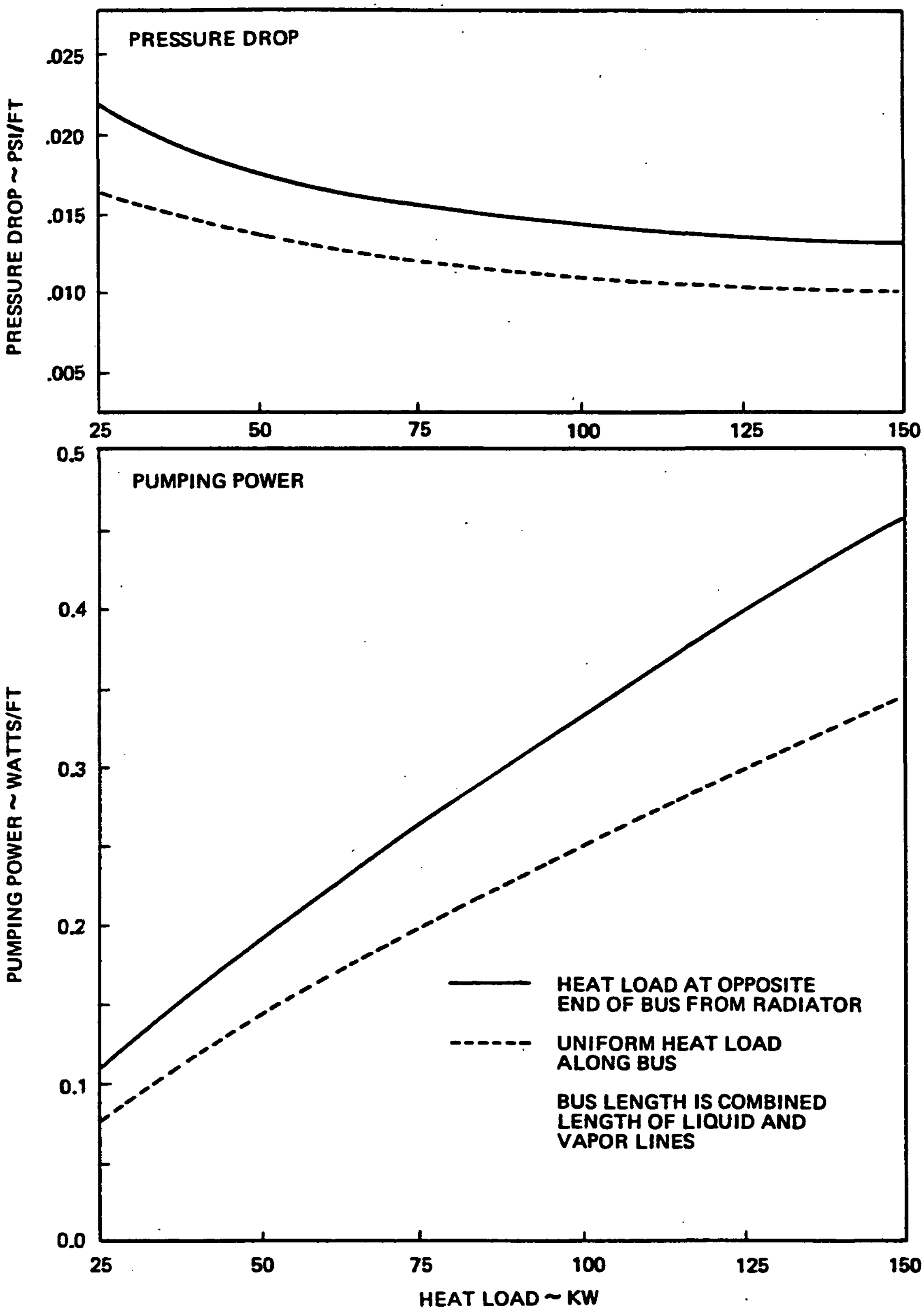


Figure 4.3-3 Optimized Pumped Two-Phase Ammonia Bus Pressure Drop and Pumping Power

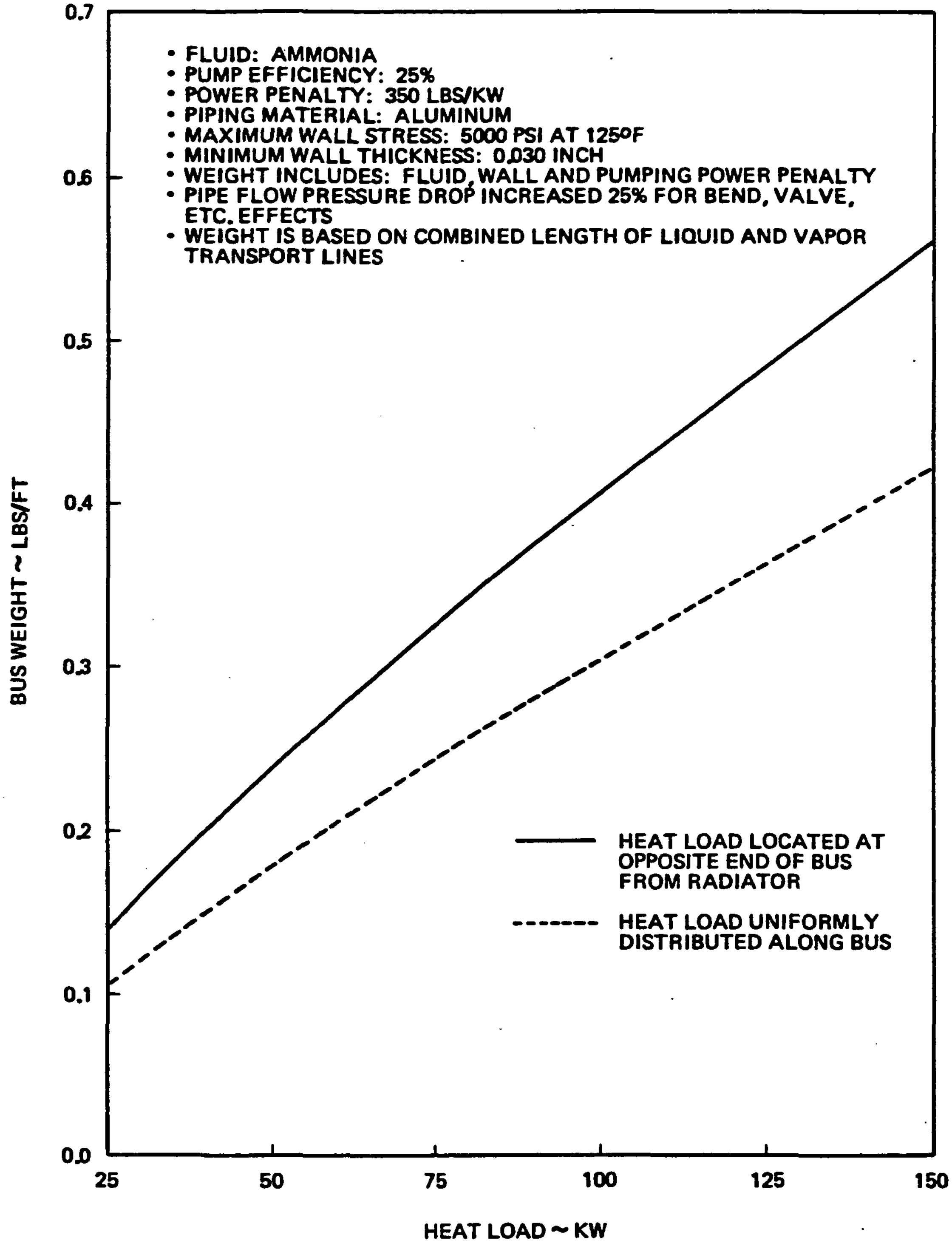


Figure 4.3-4 Pumped Two-Phase Bus Weight for Optimized Liquid and Vapor Line Sizes

$$h_w/l = \frac{FQ^{1.75}}{\rho_l g h_{fg}^{1.75}} \left[\left(\frac{\mu^{0.25}}{\rho D^{4.75}}\right)_v + \left(\frac{\mu^{0.25}}{\rho D^{4.75}}\right)_l \right]$$

where

h_w = wicking height capacity (1-g)

g = acceleration of gravity (1-g)

For a given wicking height to transport length and heat load these equations can be used to determine optimum vapor and liquid line diameters that minimize the transport loop weight. The weight and line sizing for an optimized capillary two-phase transport loop is shown in figure 4.3-5 for the high temperature bus and figure 4.3-6 for the low temperature bus. Also shown are reference points for a 300-ft transport distance with a 100 kW high temperature load and a 25 kW low temperature load. The reference points assume a wicking height capability of 1 inch under normal gravity. This corresponds to a wick pore diameter of 0.020 inches for the high temperature case and 0.025 inches for the low temperature case.

4.3.3.3 Pumped Liquid Transport Loop

The pumped liquid transport loop sizing is similar to that for the pumped two-phase case except the flow rate is an independent variable. In this study the flow rate variation is implicit in the fluid temperature change. The weight per unit transport length is given by

$$Wt/l = \rho_o t D + \frac{\pi}{4} \rho D^2 + F\left(\frac{\gamma}{\eta}\right) \left(\frac{\mu^{0.25}}{\rho^2 C_p^{2.75}}\right) \left(\frac{Q}{\Delta T}\right)^{2.75} \left(\frac{1}{D^{4.75}}\right)$$

where

Cp = specific heat of fluid

ΔT = fluid temperature change

For a given heat load to temperature change ratio, this equation can be solved iteratively to determine the optimum diameter that minimizes the weight. Figure 4.3-7 shows the optimized pumped liquid transport loop weight for Freon 11, Freon 114, and ammonia. The transport loop optimization is coupled to the optimization of other system components through its dependence on fluid temperature change.

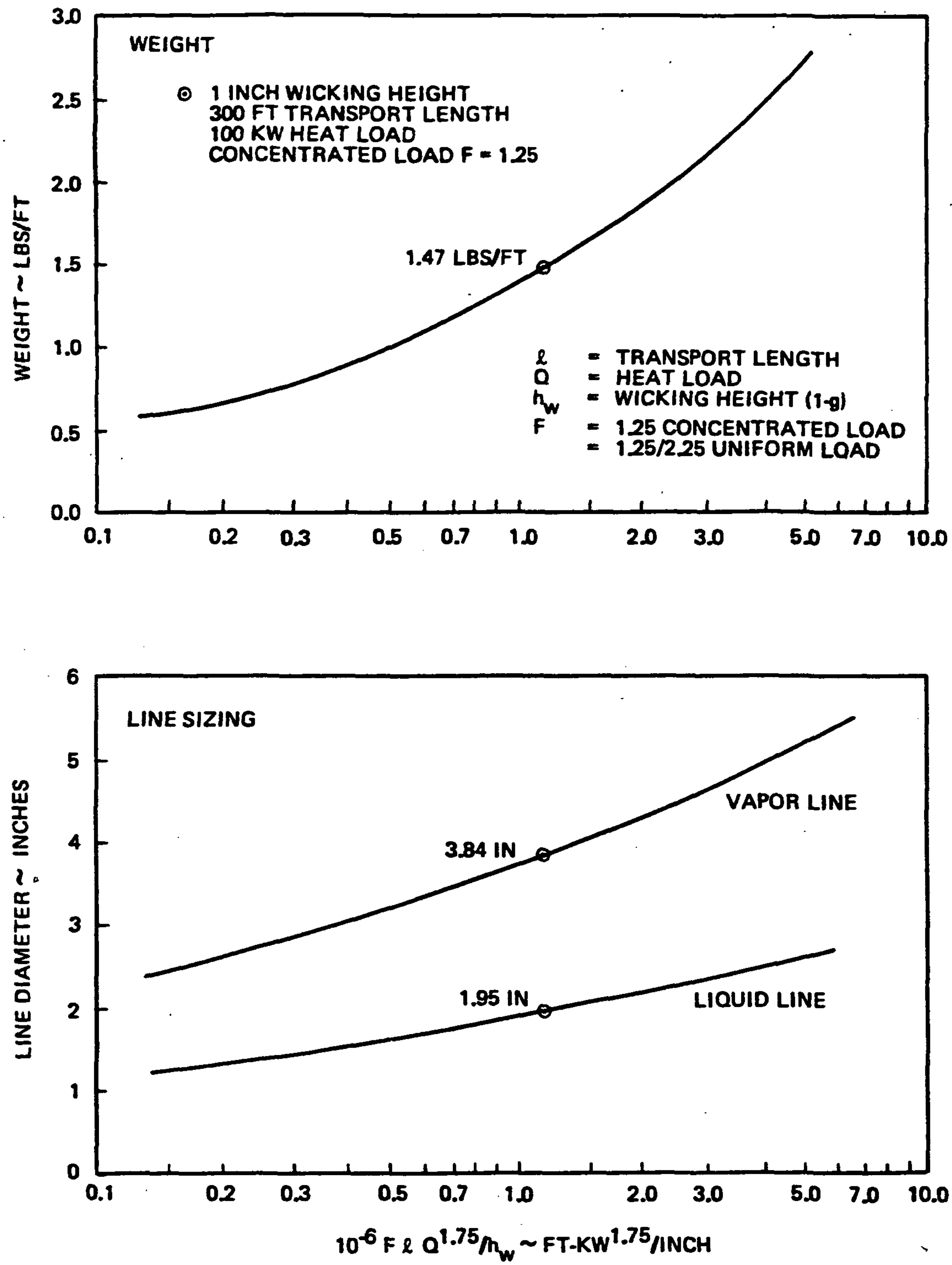


Figure 4.3-5 Optimized Capillary Two-Phase Heat Transport Loop (Ammonia) (High Temperature Bus ~ 86°F)

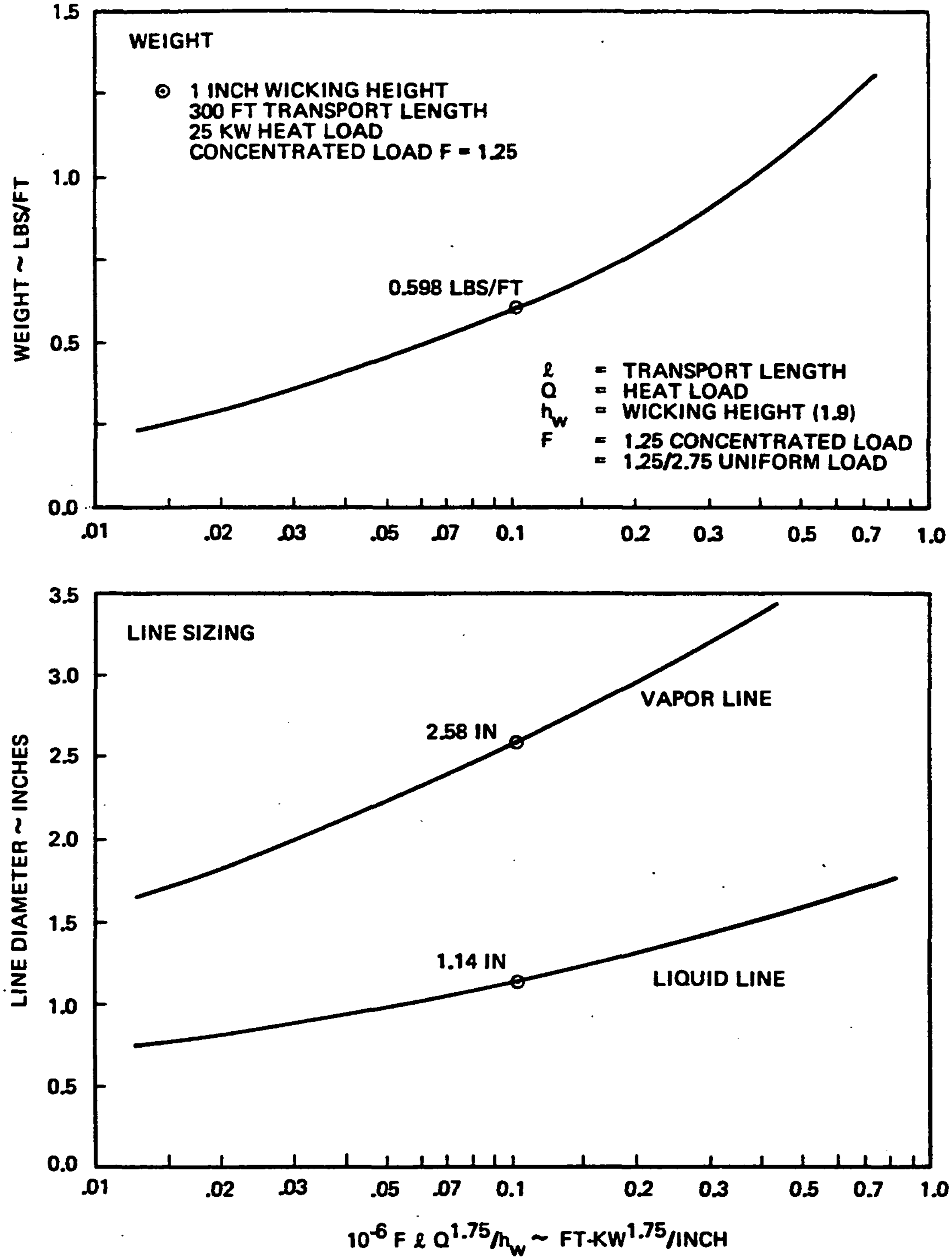


Figure 4.3-6 Optimized Capillary Two-Phase Heat Transport Loop (Ammonia) (Low Temperature Bus ~ 32°F)

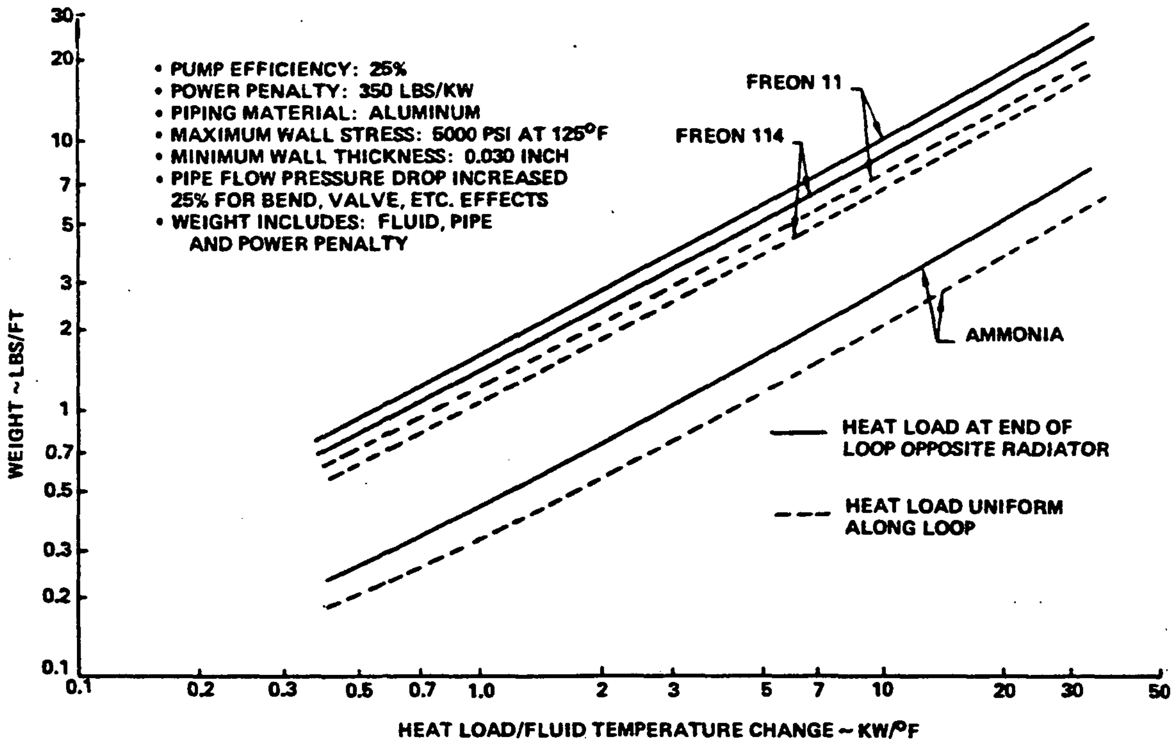


Figure 4.3-7 Pumped Liquid Loop Weight for Optimized Line Size

4.3.4 Heat Exchanger Models

The system heat exchanger weights are a major factor in system optimization and consequently in comparing different systems. Figure 4.3-8 shows the heat exchanger models used for this study. A discussion of these models is presented in the following sections.

4.3.4.1 Two-Phase Heat Exchanger

The two-phase heat exchanger model was based on the Grumman prototype design shown in figure 4.3-8 and no optimization of the design was attempted. The heat exchanger core weight, assuming a channel height of 0.2 inches (Grumman's design appears to have a total thickness of 0.2 inches) and equal volumes of metal and liquid in the liquid channel/support structure region, as

$$Wt_C = WL\,(\rho_v/75 + \rho_l/600 + \rho_o/600) \quad \text{lb}$$

W = heat exchanger width - ft

L = heat exchanger length - ft

ρ = density lbs/ft^3

subscripts v, l, o refer to vapor, liquid, and metal, respectively.

The core weight was used for comparison with liquid heat exchangers where the optimized core weight is used (sec. 4.3.4.2). The cover sheet weight was included (for both two-phase and liquid systems) in the radiator panel heat exchangers (sec. 4.3.5) where the length and width are fixed values.

The heat transfer coefficient to thermal conductivity ratio was taken as 6000 (ft)$^{-1}$. (This corresponds to a Nusselt number of 5 and a characteristic dimension of 0.01 inches which is typical of heat pipe evaporators.) Due to the liquid channels the effective heat transfer coefficient for the heat exchanger is reduced to 80% of this value. Using this effective heat transfer coefficient the heat exchanger core weight can be related to the heat transfer rate and temperature difference, for example,

$$Wt_C = \frac{\rho\,2 + \frac{1}{8}(\rho_l + \rho_o)}{105.4\,k}\left(\frac{Q}{\Delta T}\right) \quad \text{lb}$$

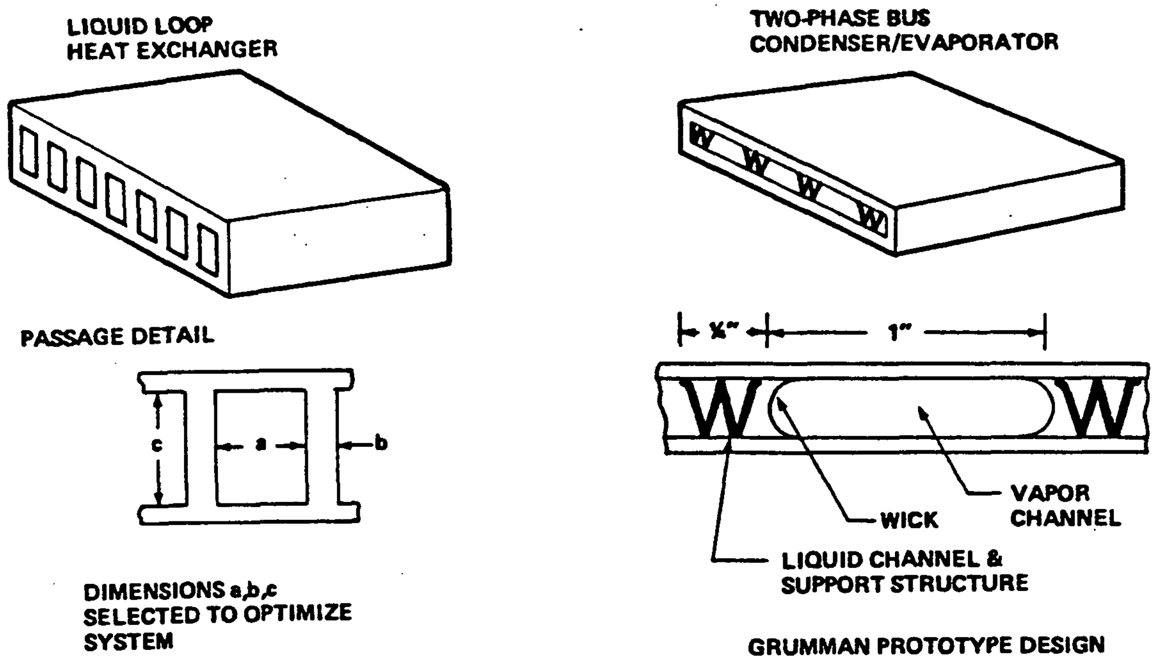


Figure 4.3-8 Heat Exchanger Models

where

k = liquid thermal conductivity (BTU/ft-hr-°F)

Q = heat transfer rate across one face of heat exchanger (kW)

ΔT = temperature difference between vapor and heat exchanger face (°F)

4.3.4.2 Single-Phase (Liquid) Heat Exchanger

The single-phase heat exchanger model (shown in figure 4.3-8) requires a detailed analyses to optimize the design parameters (a, b, and c). The core weight includes the metal, liquid, and pumping power penalty. For cases of interest the flow through the heat exchanger is laminar and the core weight is given by

$$Wt_c = cLW\rho_o \left(\frac{\rho/\rho_o + b/a}{1 + b/a}\right) + \left(\frac{\gamma}{\eta}\right)\left(\frac{8\mu}{\rho^2}\right)\frac{L}{Wc^3}(1 + b/a)(1 + c/a)^2\, m^2$$

where m = mass flow rate

For given b/a and c/a ratios the optimum c dimension for minimum weight is

$$c = \left[\left(\frac{\gamma}{\eta}\right)\left(\frac{24\mu}{\rho^2}\right)\frac{(1 + b/a)^2(1 + c/a)^2}{\rho_o(\rho/\rho_o + b/a)}\left(\frac{m}{W}\right)^2\right]^{1/4}$$

Noting that at the optimum c value, the material weight is three times the power penalty weight

$$Wt_c = 4/3\, c\, LW\rho_o \left(\frac{\rho/\rho_o + b/a}{1 + b/a}\right)$$

where c is the optimum value.

The effective heat transfer coefficient can be shown to be

$$h_{eff} = \frac{1 + (c/a)\dfrac{\tanh\alpha'}{\alpha}}{1 + b/a}\left(\frac{1 + c/a}{2c}\right) kNu$$

where Nu = Nusselt number (taken as 5 in this study)

$$\alpha = \frac{(c/a)(1 + c/a)}{(b/a)}\left(\frac{k}{k_o}\right)\cdot\frac{Nu}{4}$$

k_o = thermal conductivity of metal

$\alpha' = \alpha$ for one side only heat transfer

$= 2\,\alpha$ for two side heat transfer

The effective conductance to weight ratio is (using the optimum c value)

$$\frac{h_{eff}A}{Wt} = \frac{3}{8}\,kNu\,\frac{\rho}{\rho_o}\left(\frac{\rho_o}{24Y}\right)^{1/2}\frac{W}{m}\,\xi$$

where

$$\xi = \frac{1 + (c/a)\,\dfrac{\tanh\alpha'}{\alpha}}{(1 + b/a)(\rho/\rho_o + b/a)^{1/2}}$$

$$A = LW$$

For a given c/a ratio, the optimum b/a ratio can be found that maximizes ξ, and thus minimizes the heat exchanger weight to effective conductance ratio.

As the c/a ratio increases the heat exchanger weight to effective conductance ratio asymptotically approaches a minimum value. For c/a large with respect to unity

$$\xi = \frac{1 + 2\left(\dfrac{k_o}{kNu}\right)^{1/2}\left(\dfrac{b}{a}\right)^{1/2}}{(1 + b/a)\,(\rho/\rho_o + b/a)^{1/2}}$$

and the optimum b/a is independent of c/a as is the heat exchanger weight to effective conductance ratio. This approximation was used for all liquid heat exchangers except for those coupled to the radiator panels where, due to the coupling with other conductances, an optimum value of c/a exists (sec. 4.3.5.2).

The heat exchanger core weight can be written as

$$Wt_c = \left(\frac{h_{eff}A}{\psi}\right)\frac{Q}{\Delta T}$$

where Q = heat transfer rate

$$\psi = \frac{3}{8}\,W\,cp\,kNu\left(\frac{\rho}{\rho_o}\right)\left(\frac{\rho_o\eta}{24\mu}\right)^{1/2}\xi_{max}$$

The liquid heat exchanger weight depends on the wall boundary condition. For a uniform heat flux boundary condition

$$h_{eff}A = \frac{Q}{\Delta T_w}$$

A = heat transfer area

ΔT_w = temperature difference between wall and fluid (constant for constant Nusselt number)

The heat exchanger weight for this case is then

$$Wt_C = \theta \left(\frac{Q}{\Delta T}\right)^2 \left(\frac{\Delta T}{\Delta T_w}\right)$$

where

θ = $1/\psi$ for one side heat transfer

= $1/2\psi$ for two side heat transfer

This boundary condition case was used for cold plate heat exchangers and balanced counterflow heat exchangers.

For a uniform wall temperature case

$$h_{eff}A = \frac{Q}{\Delta T} \ln\left(1 + \frac{\Delta T}{\Delta T_w}\right)$$

where, in this case,

ΔT_w = smallest temperature difference between wall and fluid

The heat exchanger weight for this case is then

$$Wt_C = \theta \left(\frac{Q}{\Delta T}\right)^2 \ln\left(1 + \frac{\Delta T}{\Delta T_w}\right)$$

This boundary condition case was used for liquid loop heat exchangers interfacing with a two-phase heat exchanger.

4.3.5 Radiator Sizing

The Grumman space constructable radiator was used as the radiator model for both two-phase and pumped liquid-loop heat transport systems analyses. This radiator model is shown in figure 4.3-9. Heat pipe radiator panels are clamped together with a heat exchanger unit sandwiched between them. The required radiator area is provided by placing the required number of radiator panel/heat exchanger units adjacent to each other. The radiator panel properties (size, weight, emissivity, fin effectiveness, panel, and contact thermal conductances) are based on Grumman's design values. The environmental radiation sink temperature was set at 415°R for the present study. This value is representative of a steerable radiator in low earth orbit with a completely degraded ($_s$ = ε) thermal coating.

4.3.5.1 Two-Phase System Radiator

The two-phase bus/radiator panel interface heat exchanger used for the radiator analyses is described in section 4.3.4.1. The thermal balance for one heat exchanger unit coupled with two radiator panels is

$$Q = 2K(T_B - T_R) = 2\,\varepsilon\sigma\eta A(T_R{}^4 - T_S{}^4)$$

Q = heat rejection rate

K = Thermal conductance from vapor to one radiator panel

$$= \frac{1}{\frac{1}{K_F} + \frac{1}{K_C} + \frac{1}{K_{12}}}$$

K_F = vapor to heat exchanger for conductance

K_C = contact conductance between heat exchanger face and radiator panel (1167 BTU/HR-°F)

K_R = radiator panel conductance (1000 BTU/HR °F)

ε = panel emissivity (0.8)

η = fin effectiveness (0.58)

A = panel area (100 ft^2)

T_B = two-phase bus temperature

T_R = radiator fin root temperature

T_S = sink temperature (415°R)

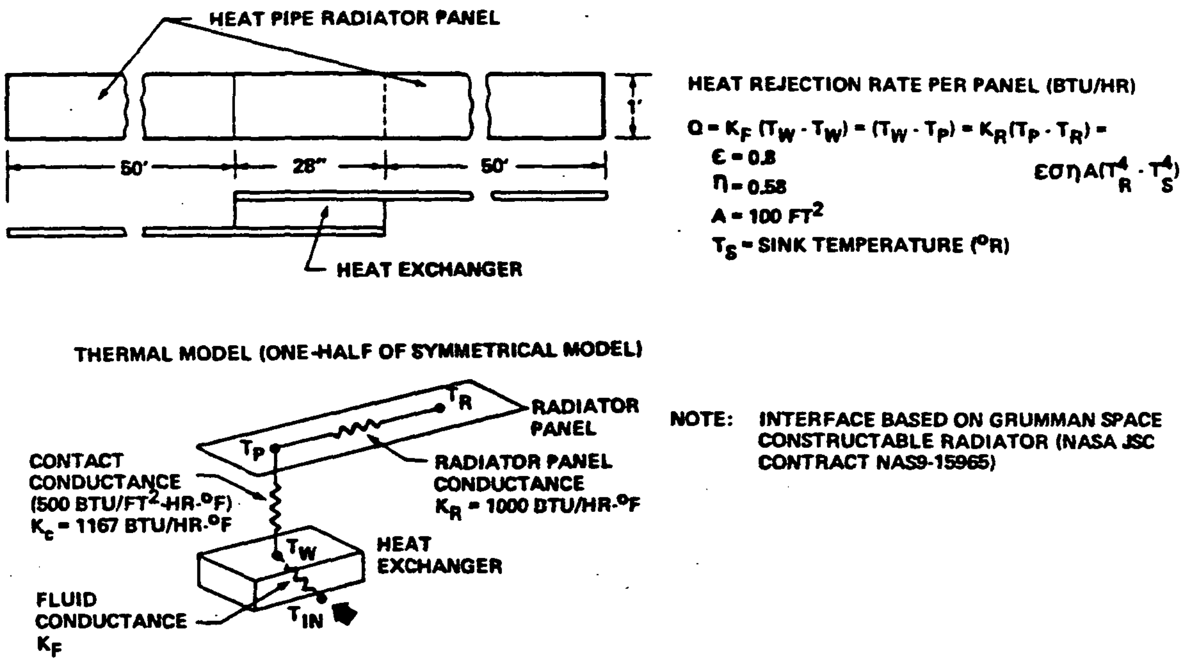


Figure 4.3-9 Heat Transport Loop/Radiator Interface

The vapor to heat exchanger conductance K_F for ammonia is 3200 BTU/HR-°F. This gives an overall conductance K of 461 BTU/HR-°F.

For a given bus temperature T_B an iterative solution to the thermal balance provides the heat rejection rate per radiator panels/heat exchanger unit. The radiator system weight required to reject this heat load consists of heat exchanger and radiator panels weight. The heat exchanger weight for ammonia as a working fluid and aluminum as the metal is, including 0.05-inch face sheets, 4.2 lb. The weight of the two radiator panels (1.2 lb/ft^2) is 120 lb. The radiator system weight per unit heat rejection rate is the total weight (124.2 lb) divided by the heat rejection rate Q found from the thermal balance equation. Figure 4.3-10 shows the resulting radiator system weight as a function of two-phase bus temperature.

4.3.5.2 Pumped Liquid Loop System Radiator

The pumped liquid loop/radiator panel interface heat exchanger model is described in section 4.3.4.2. The thermal balance for one heat exchanger unit coupled to two radiator panels is (similar to two-phase system).

$$Q = 2K\,(T_{in} - T_R) = 2\,\varepsilon\sigma\eta \cdot A(T_R^4 - T_S^4)$$

where T_{in} is the fluid inlet temperature to the heat exchanger unit and the overall thermal conductance is defined as previously with the fluid conductance K_F now given by

$$K_F = \frac{mCp}{2}\left(1 - e^{\frac{-2h_{eff}A_c}{mCp}}\right)$$

m = mass flow rate through unit

A_c = contact area (2.33 ft^2)

The radiator system weight includes, as before, the radiator panels and heat exchanger weight. The heat exchanger weight consists of cover sheets (identical to two-phase analysis) and core weight as described in section 4.3.4.2. The liquid loop system radiator analyses is more complicated than that for the two-phase system because the mass flow rate through the radiator panel heat exchanger units depends on the flow routing and the overall fluid temperature change. An additional complication is the weight optimization for each flow condition.

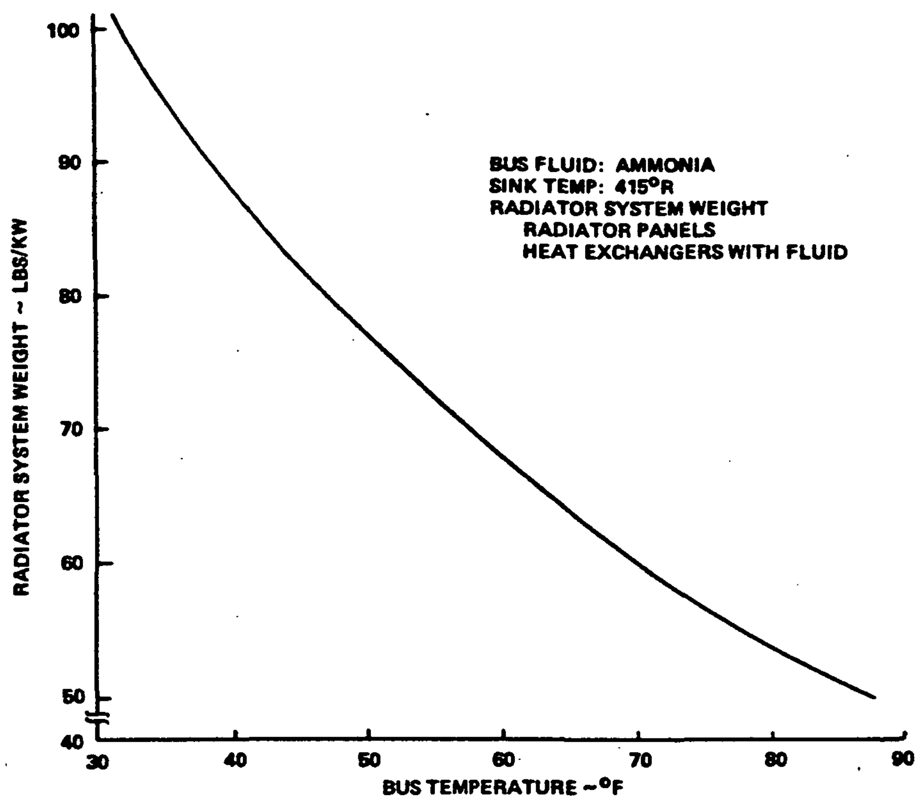


Figure 4.3-10 Radiator System Weight for Two-Phase Bus

The pumped liquid-loop system radiator optimization was performed as follows.

1. Select heat rejection rate for a set of radiator/heat exchanger units connected in series flow. This fixes the relationship between mass flow rate and fluid temperature change for a given fluid.

2. Select a fluid inlet temperature to the radiator system.

3. Select the overall fluid temperature change through the set of radiators.

4. For a given heat exchanger c/a ratio determine the optimum b/a ratio (iterative procedure) and calculate the fluid conductance K_F and heat exchanger weight.

5. Determine number of radiator panels/heat exchanger units required to reject the specified heat load. This is accomplished by iteratively solving the thermal balance equation for each unit. The radiator system fluid inlet temperature is used as the inlet temperature to the first unit and the first unit's outlet temperature is used as the inlet for the second unit, etc. When the total temperature change exceeds the specified value, the final unit is prorated (i.e., fraction of a unit) to provide the specified temperature change.

6. Calculate radiator system weight by multiplying the required number of units times the weight per unit.

7. Determine minimum radiator system weight by incrementing heat exchanger c/a value (using an appropriate algorithm) and iterating (from step d.) until the optimum c/a is found.

8. Select new overall fluid temperature change and repeat calculation (from step c.) to determine the minimum weight for this condition. An iterative procedure could be used here to find the optimum temperature change for the radiator system. However, because the fluid temperature change affects the weight of other system components, the optimum change must be based on the overall system optimization.

9. Select a new inlet fluid temperature and repeat calculations from step b. The radiator system weight decreases monotonically with increased inlet temperature. The absolute maximum inlet temperature is limited by the allowable equipment temperature and the optimum value must be determined on an overall system weight basis.

10. Select a new heat rejection rate for a set of radiator/heat exchanger units and repeat calculation from step a. This would allow the optimum flow routing to be determined for various conditions.

A limited investigation of the effects of flow routing showed the radiator weight per unit heat rejection rate to be insensitive to specified heat rejection per set of radiation panel/heat exchanger units over a wide range of values. Consequently, a convenient (and near optimal) value of 25 kW per set of series connected units was chosen for this study.

The pumped liquid loop system radiator optimization provides the minimum radiator system weight as a function of radiator inlet temperature and overall fluid temperature change. Figure 4.3-11 shows an example of optimum radiator system weight for an inlet temperature of 70°F. As noted previously, the optimum inlet and outlet temperatures must be determined from an overall system optimization.

4.3.6 Pressurized Module Pumped Water Loop

The manned (pressurized) modules of the space station have a pumped water heat transport loop that transports waste heat to the main heat transport system by means of an interface heat exchanger. In order to compare two-phase and pumped liquid main transport systems, these internal water loops and associated heat exchangers must be included in the system analyses.

4.3.6.1 Two-Phase Main Heat Transport System

Figure 4.3-12 shows the model used to analyze the water transport loop coupled to a two-phase bus. The water loop is coupled to the two-phase bus by means of an interface heat exchanger. One side of this heat exchanger is a two-phase heat exchanger (sec. 4.3.4.1) and the other side is a liquid heat exchanger (sec. 4.3.4.2). These heat exchangers are assumed to be in intimate contact (or an integram unit) so that there is no temperature drop across the interface itself. The heat load to the water loop is applied

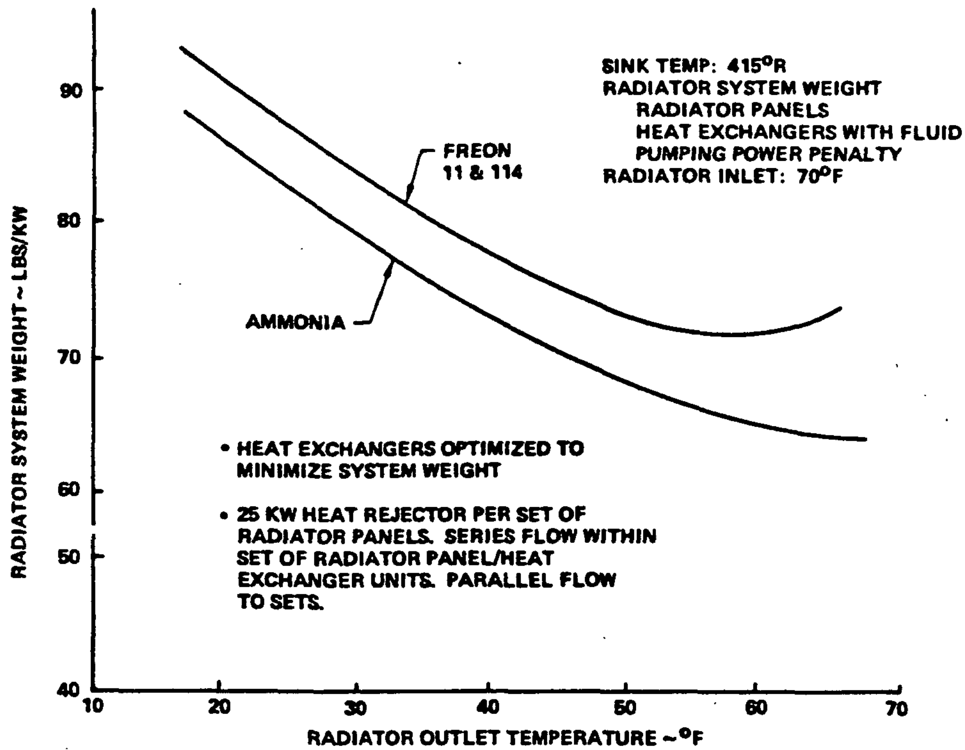


Figure 4.3-11 Radiator System Weight for Liquid Loop Heat Transport System

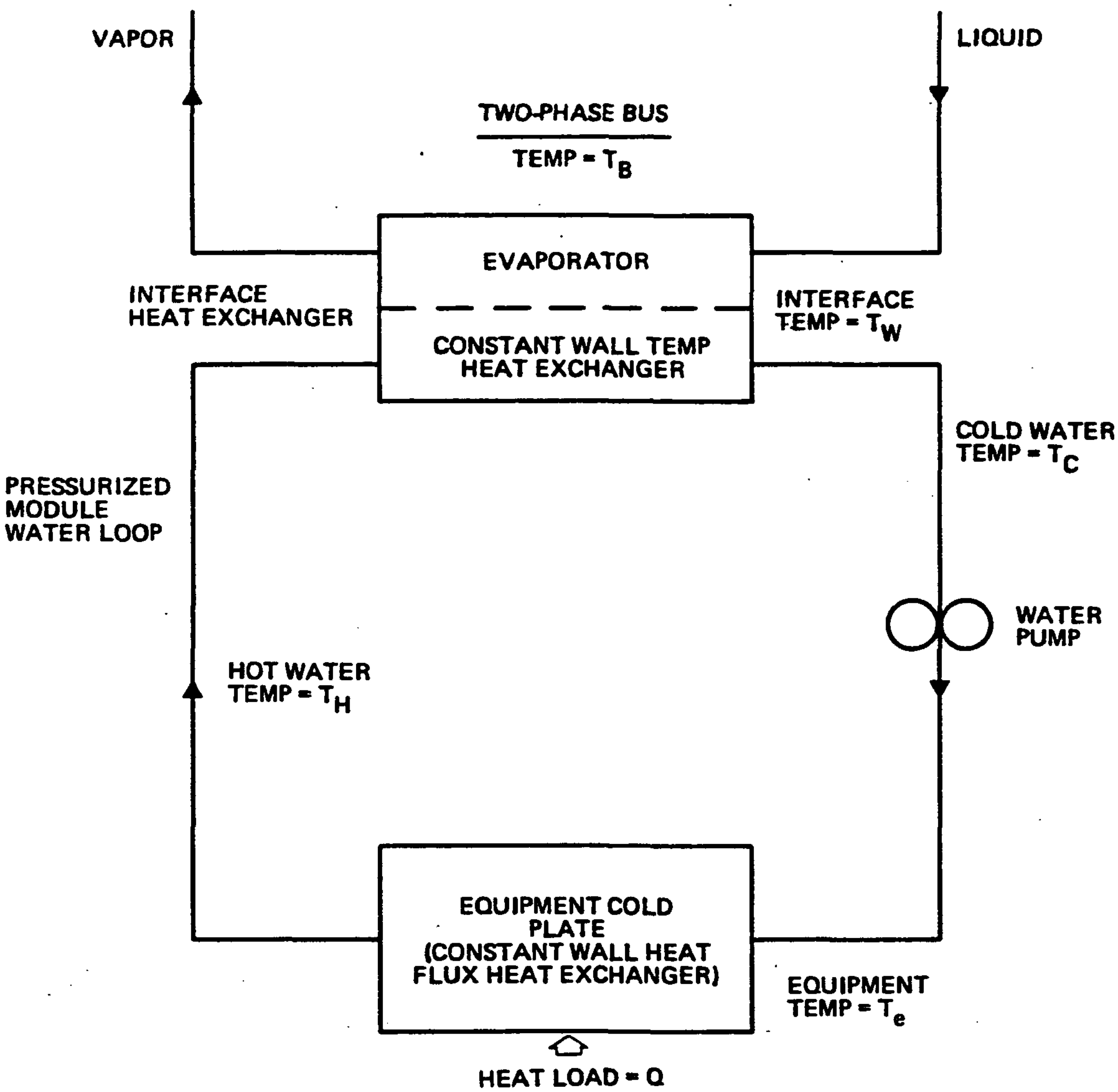


Figure 4.3-12 Two-Phase Bus/Water Loop Interface

through a cold plate heat exchanger unit. The weight of the pressurized module loop consists of the pumped water loop itself (lines, water, pump power penalty) and the heat exchanger units.

The water loop itself can be optimized as a function of heat load to water temperature change as outlined in section 4.3.3.3. The heat exchangers can be optimized, as a set, in terms of heat load, water temperature change, and equipment to bus temperature difference. The total weight of the heat exchangers is (see sec. 4.3.4)

$$Wt_{HX} = \left(\frac{Q}{T_e - T_B}\right) \frac{\zeta}{(1-\phi)(1-\xi)} - \frac{\theta}{\tau^2}\left(\frac{Q}{T_e - T_B}\right) \ln\left(1 - \frac{\tau}{\xi(1-\phi)}\right) + \frac{\theta}{\tau}\left(\frac{Q}{T_e - T_B}\right)\frac{1}{\phi}$$

Q = heat load

T_e = equipment temperature

T_B = bus temperature

$\zeta = \dfrac{\rho_v + (\rho_l + \rho_o/8)}{105.4k}$ (see sec. 4.3.4.1)

θ = constant for liquid heat exchanger (see sec. 4.3.4.2)

$\tau = \dfrac{\Delta T}{T_e - T_B}$

ΔT = water temperature change

$\phi = \dfrac{T_e - T_H}{T_e - T_B}$

T_H = hottest water temperature

$\xi = \dfrac{T_H - T_W}{T_H - T_B}$

T_W = Interface temperature (i.e., two-phase heat exchanger wall temperature)

The temperature ratio variables (ξ, ϕ, and τ) can be optimized to give a minimum total heat exchanger weight for a given heat load, bus, and equipment temperatures. For these given conditions, the weight of the water loop is based on the water temperature difference corresponding to the optimized value for the heat exchangers. A more refined analysis would include the water loop weight in the optimization of . The overall effect of this refinement, however, is expected to be small.

4.3.6.2 Pumped Liquid-Loop Heat Transport System

There are two cases to consider for the pumped liquid-loop heat transport system interface with the pressurized modules. One case is that in which there are separate heat transport systems for the high- and low-temperature heat loads. The other case is where

the same loop is used for both high and low temperature loads. The models for these cases are shown in figure 4.3-13.

The analysis of the separate loop case is similar to that for the two-phase system described in the previous section. In this case, the interface heat exchanger is a balanced counterflow device and the optimized set of heat exchangers weight can be written analytically as

$$Wt_{HX} = \left(\frac{Q}{\Delta T}\right)\left(\frac{Q}{T_e - T_{in}}\right)\left(\theta_m^{1/2} + 2\theta_w^{1/2}\right)^2$$

where T_{in} = radiator inlet temperature and subscripts m and w refer to the main loop and water heat exchangers, respectively.

The total heat exchanger weight for the single-loop system includes that of the humidity control heat exchanger in addition to that of equipment cold plate and interface heat exchangers. The total heat exchanger weight for this case is

$$Wt_{HX} = \frac{1}{\tau}\left(\frac{Q}{T_e - T_{in}}\right)^2 \quad \frac{(\theta_m^{1/2} + \theta_w^{1/2})^2}{(1-\phi)} + \frac{\theta_w\,(Q_e/Q)}{\phi}$$

$$+ \frac{\theta_w\,(Q_{HC}/Q)}{\phi + (Q_e/Q) \quad - \left(\frac{T_e - T_{HC}}{T_e - T_{in}}\right)}$$

$\tau = \dfrac{\Delta T}{T_e - T_{in}}$

ΔT = water temperature change

Q = total heat load

Q_e = equipment heat load

Q_{HC} = humidity control heat load

T_{HC} = humidity control temperature

$\phi = \dfrac{T_e - T_H}{T_e - T_B}$

For given Q_e, Q_{HC}, T_e, T_{HC}, and T_{in} an optimum ϕ value can be found that minimizes the weight at a given value of the parameter τ . The range of values for this parameter is restricted by the constraints that the main loop liquid entering the interface heat exchanger must be above the freezing point of water and the water temperature leaving

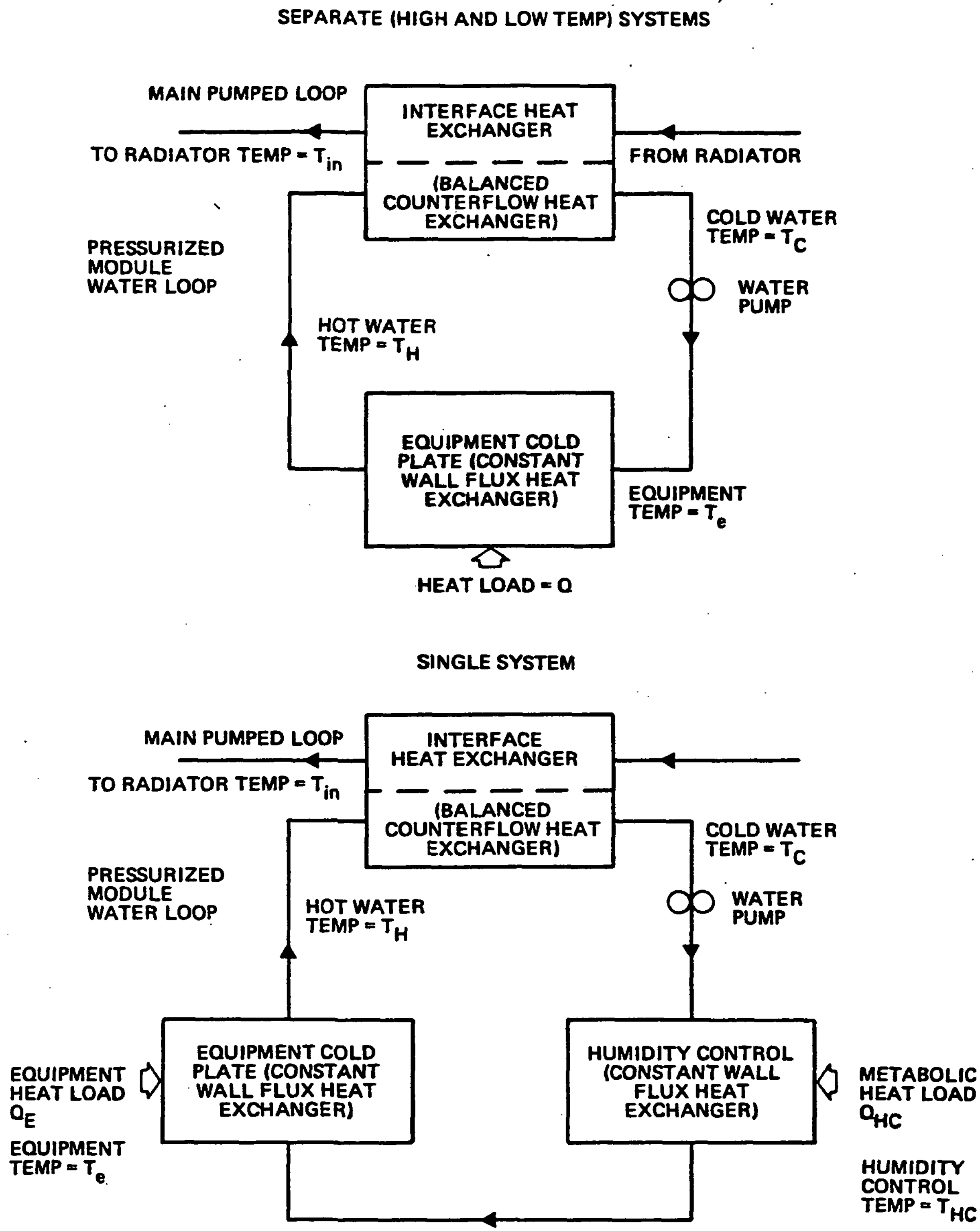


Figure 4.3-13 Pumped Liquid Loop/Water Loop Interface

the humidity control unit must be less than the humidity control temperature. These limits are

$$\left(\frac{Q}{Q_e}\right)\left(\frac{T_{in}-T_{HC}}{T_e-T_{in}}\right) < \tau < \frac{T_{in}-32^oF}{T_e-T_{in}}$$

For given equipment specifications (Q_e, Q_{HC}, T_e, T_{HC}), the total pressurized module water loop weight (heat exchangers plus loop itself) depends on the radiator inlet temperature T_{in} and water temperature change. The optimum value of these parameters must be based on total system weight considerations.

4.3.7 Space Station Thermal Control System Sizing

4.3.7.1 System Definition

In order to compare space station heat transport systems a baseline space station must be defined. The following space station parameters were used as a baseline for comparison:

1. Total heat load: 125 kW.
2. Round trip heat transport distance: 300 ft.
3. Radiation sink temperature: -45^{o}F (415^{o}R).
4. Equipment temperature: 85^{o}F.
5. Battery and humidity control temperature: 40^{o}F.
6. Heat load distribution:
   a. Equipment (85^{o}F) 100 kW.
      (1) five unpressurized 10 kW cold plates.
      (2) five pressurized module 10 kW cold plates.
   b. Battery (40^{o}F) 20 kW.
      (1) two unpressurized 10 kW cold plates.
   c. Humidity control (40^{o}F) 5 kW.
      (1) five pressurized module 1 kW units.
   d. Load distribution along loop assumed to be midway between uniform and concentrated distribution cases.
   e. Separate high and low temperature two-phase heat rejection systems.
   f. Capillary system wicking height of 1 inch under normal gravity (1-g).
   g. Single pumped liquid loop system (battery cold plate in series flow downstream of radiator in order to maintain a high radiator inlet temperature and that allows a reduction of radiator area).

h. Water heat transport loop inside pressurized modules.
i. Materials: aluminum for main transport loop and stainless steel for water loop.
j. Main transport fluid: ammonia for two-phase systems and Freon 11 or ammonia for pumped liquid loop systems.

The heat load and transport distance are representative of a relatively mature space station. The baseline system assumes use of solar panels with battery storage. (A system utilizing fuel cells would require consideration of a higher temperature heat source.) Separate high and low temperature two-phase systems are used to minimize total system weight. The pumped liquid loop systems have the entire flow from the radiator pass through the battery cold plates before passing through any other heat exchangers. This constraint, on battery placement and flow routing, allows the radiator inlet temperature to be maintained at a high level, which minimizes the radiator size and weight. The pumped liquid loop is representative of current state of the art and the pumped liquid ammonia loop system allows direct comparison with the two-phase ammonia systems.

4.3.7.2 Two-Phase System Optimization

The two-phase bus (pumped and capillary), equipment cold plates, pressurized module heat exchangers and water loop, and radiator weights were calculated for the baseline space station at various bus temperatures. (The details of these calculations were described in the previous sections.) Figure 4.3-14 shows the high temperature system elements and total weight as a function of bus temperature. The pumped and capillary two-phase systems are identical except for the bus weight itself. The minimum weight for both systems occurs at a bus temperature of about 70°F. Detailed sizes, weights, and temperatures are shown in the high temperature system schematic (fig. 4.3-15).

The low temperature system element weights are shown in figure 4.3-16 as a function of bus temperature. The minimum total system weight occurs at a bus temperature of about 36°F. A detailed schematic for this optimum low temperature system is shown in figure 4.3-17.

4.3.7.3 Pumped Liquid-Loop System Optimization

For the given baseline space station conditions the pumped liquid loop systems have an optimum liquid temperature change that minimizes the system weight at a given inlet temperature to the radiator. Figure 4.3-18 shows the pumped Freon system element

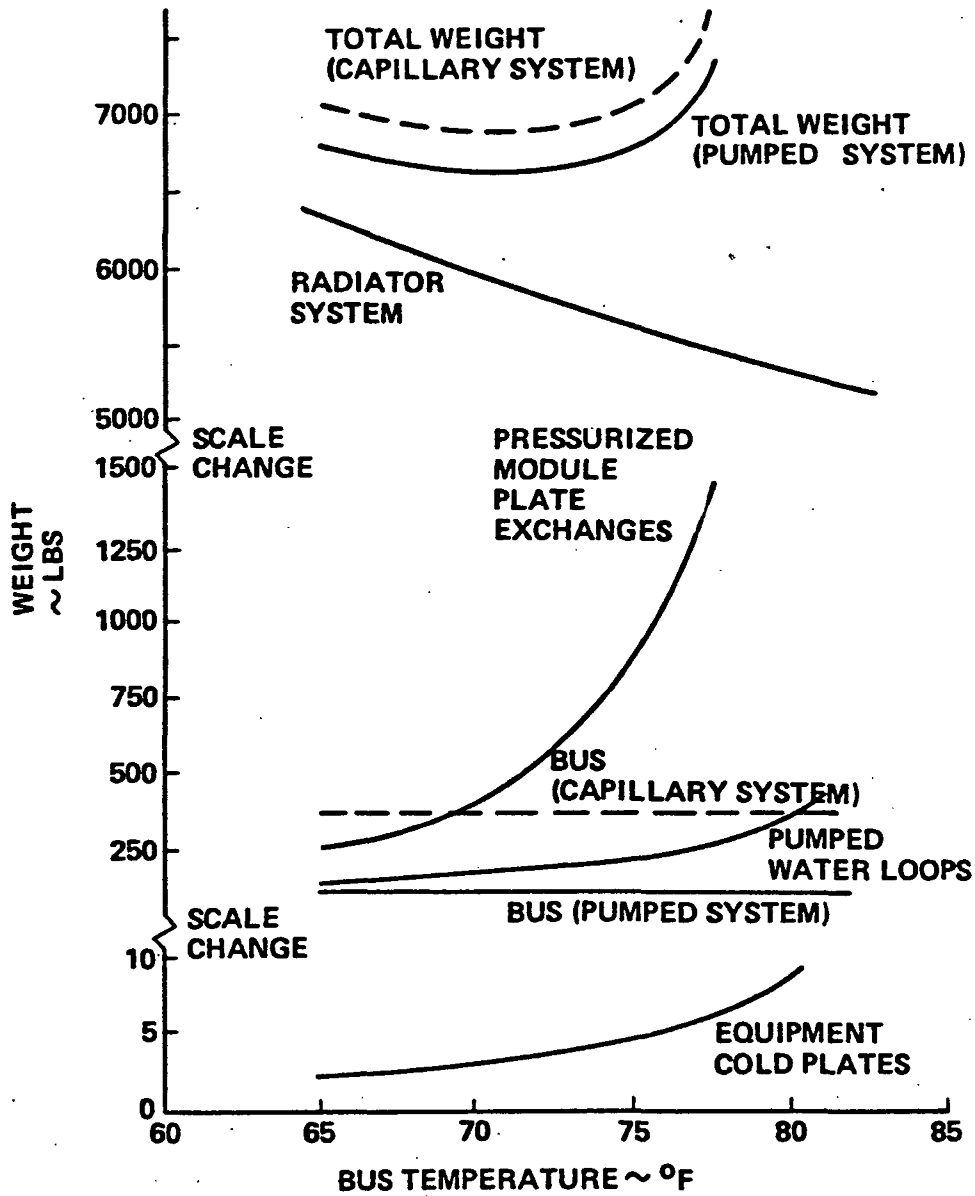
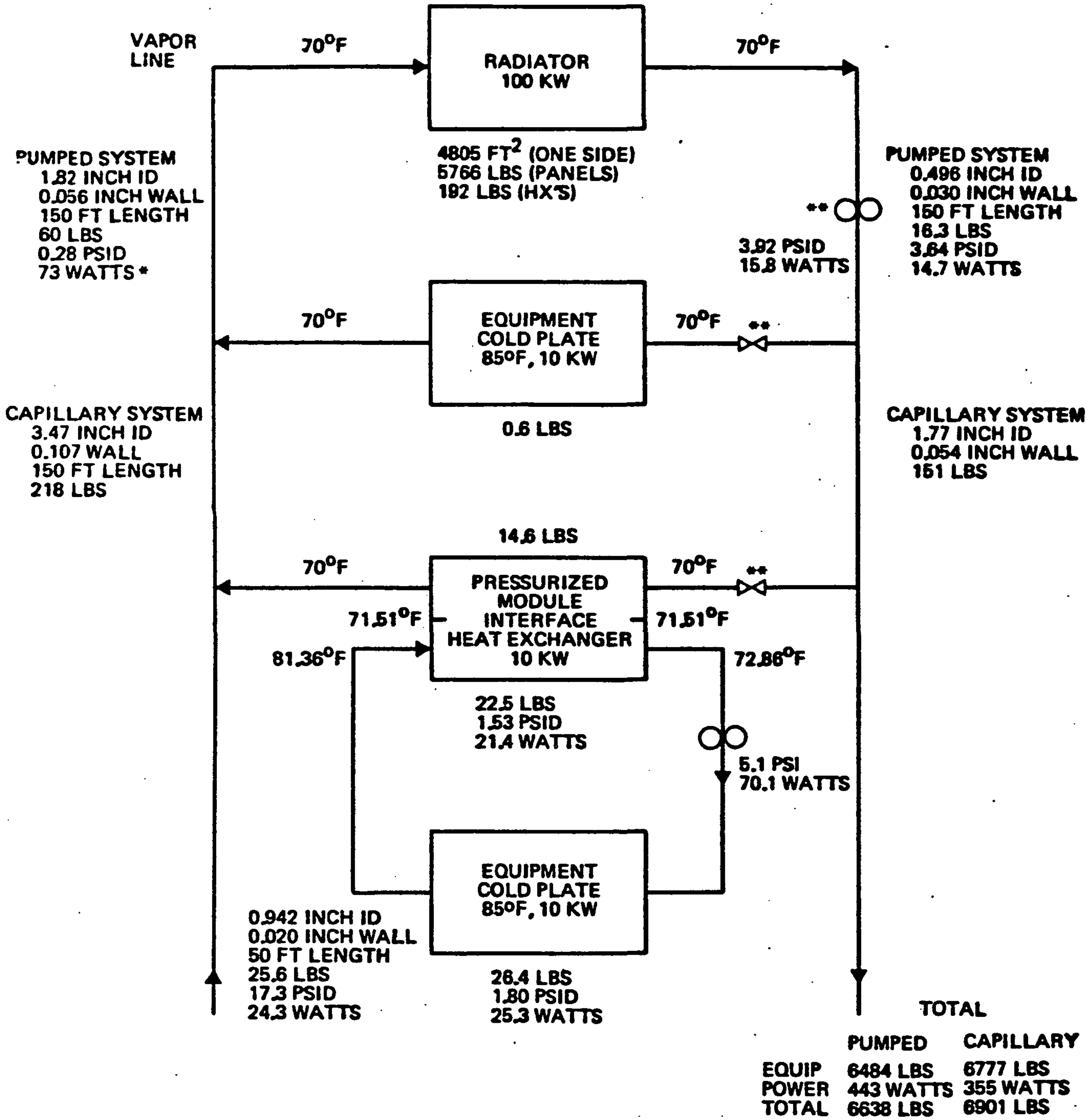


Figure 4.3-14 High Temperature Two-Phase Ammonia System



* INCLUDED AS PUMP POWER IN ANALYSES, HOWEVER, MOST OF POWER (71.9 WATTS) PROVIDED BY WASTE HEAT

** PUMPED SYSTEM ONLY

Figure 4.3-15. Two-Phase Ammonia High Temperature System Schematic

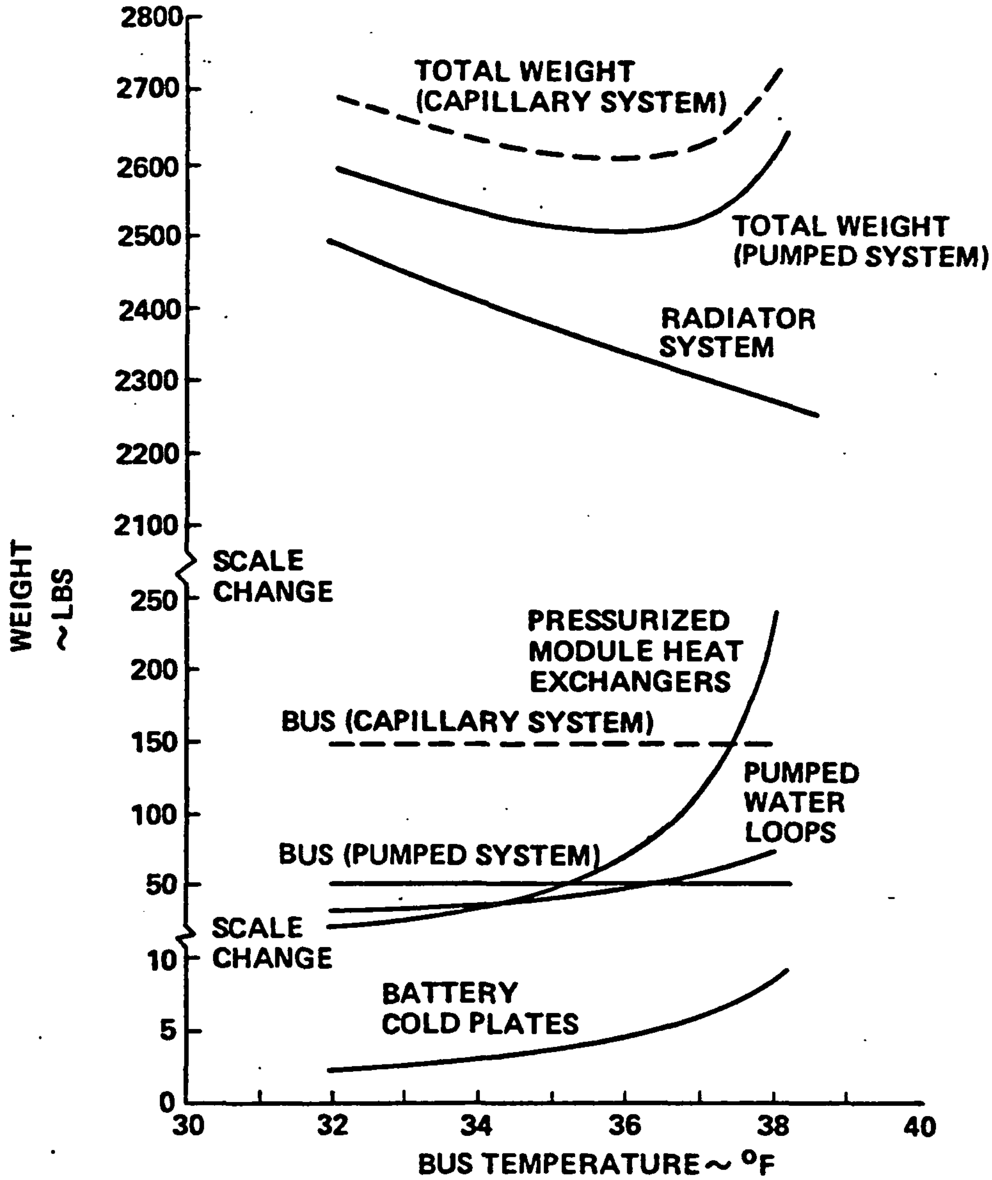
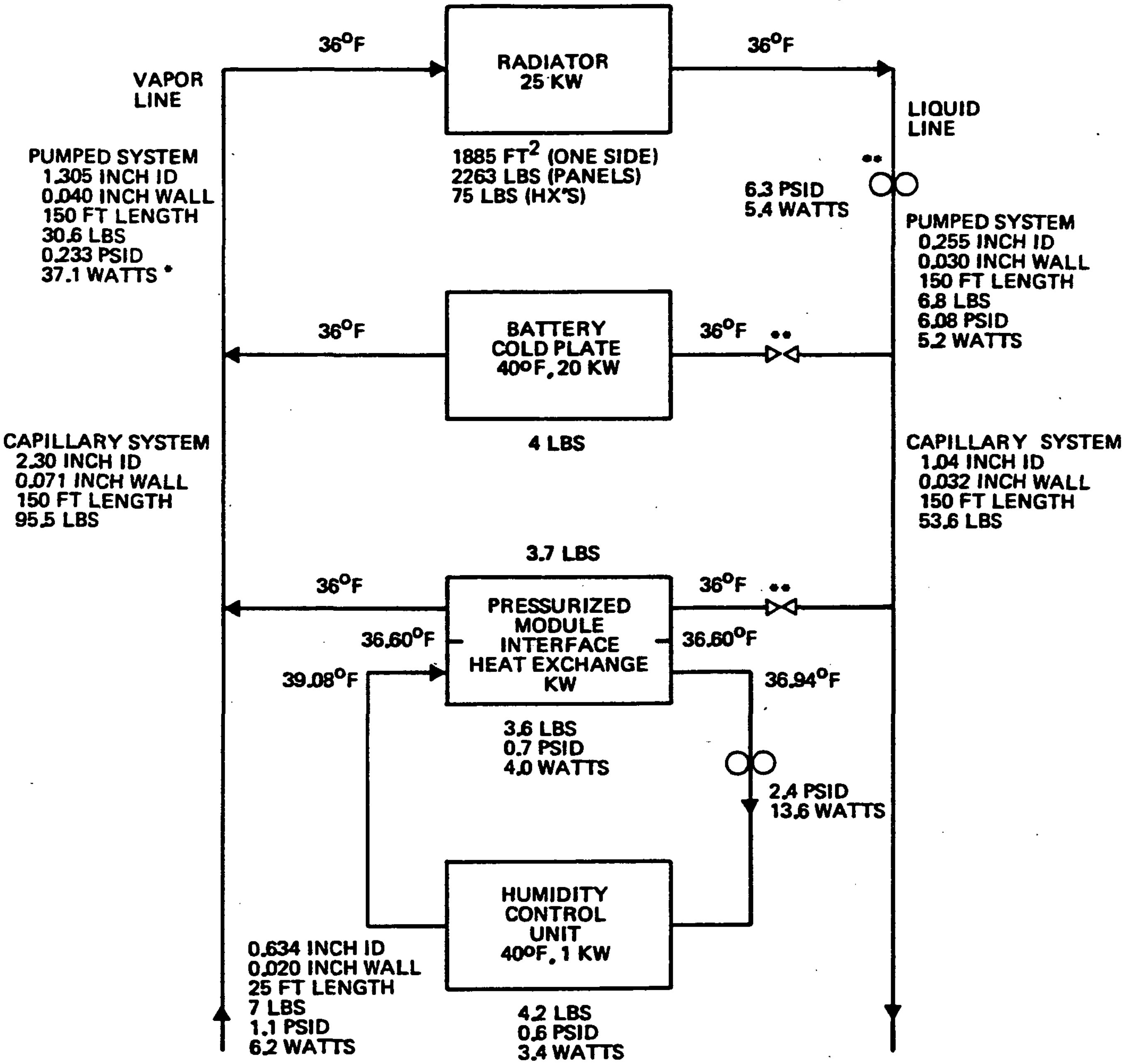


Figure 4.3-16 Low Temperature Two-Phase Ammonia System



TOTAL

	PUMPED	CAPILLARY
EQUIP	2472 LBS	2533 LBS
POWER	110 WATTS	68 WATTS
TOTAL	2510 LBS	2607 LBS

* INCLUDED AS PUMP POWER IN ANALYSES, HOWEVER, MOST OF POWER (36.9 WATTS) PROVIDED BY WASTE HEAT.

** PUMPED SYSTEM ONLY

Figure 4.3-17 Two-Phase Ammonia Low Temperature System Schematic

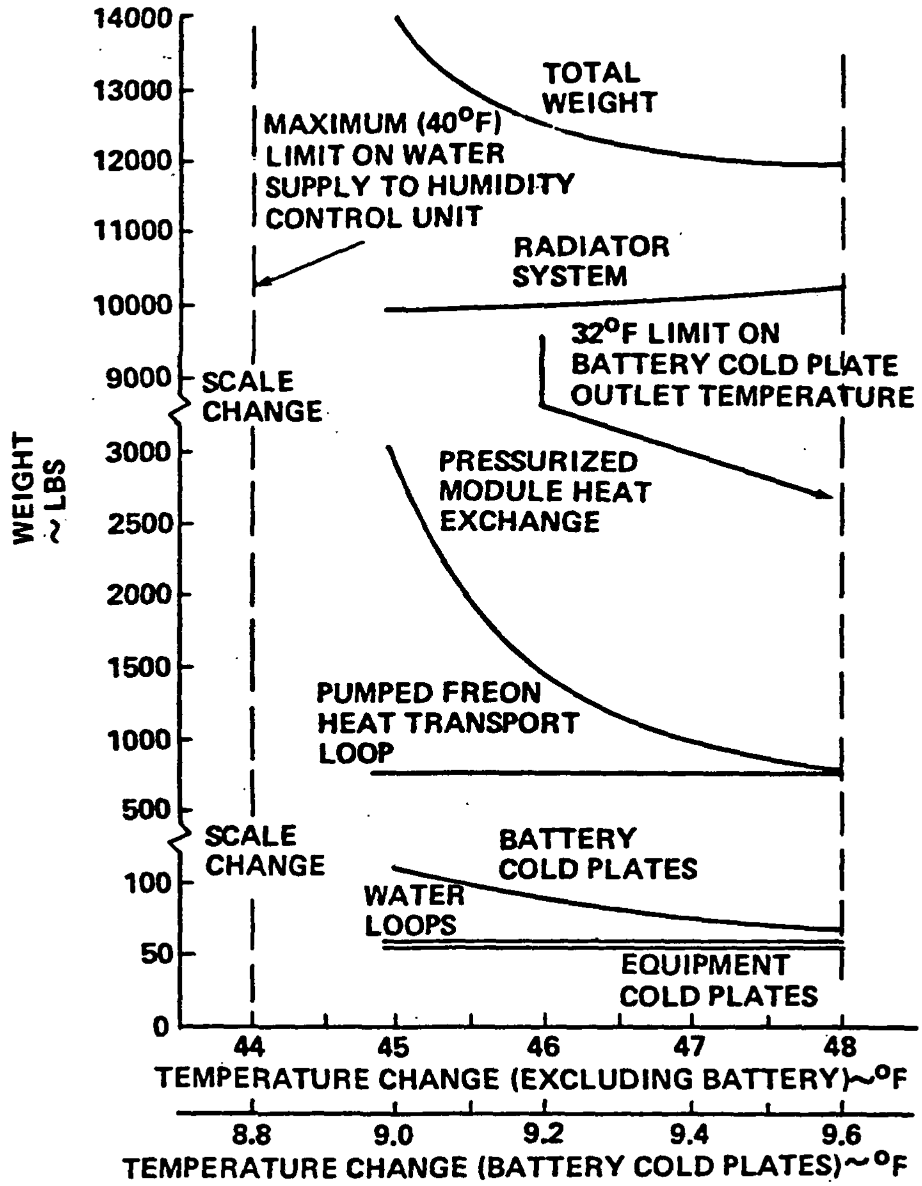


Figure 4.3-18 Pumped Liquid Loop (Freon 11 with 80°F Radiator Inlet)

weights as a function of fluid temperature changes for a radiator inlet temperature of 80°F. (The details of the weight calculations were described in the previous sections.) The fluid temperature change is constrained by the 40°F humidity control temperature and the 32°F freezing point of water in the pressurized module loop. The total system weight reaches a minimum at the 32°F battery cold plate outlet temperature limit. Figure 4.3-19 shows the pumped ammonia system element weights for identical 80°F radiator inlet temperature. In this case the optimum fluid temperature change occurs before the 32°F battery cold plate outlet temperature limit is reached.

Figure 4.3-20 shows the minimum system weight as a function of radiator inlet temperature for ammonia and Freon systems. The 80°F inlet temperature is close to optimal for both fluids. Detailed schematics for the optimum (80°F radiator inlet) Freon 11 and ammonia pumped loop systems are shown in figures 4.3-21 and 4.3-22, respectively.

4.3.8 Effect of Two-Phase Water System in Pressurized Modules

The interface between the two-phase heat transport bus and the pumped water loops in the pressurized modules results in a lowering of the bus temperature in order to minimize system weight. The reason for this is that the water temperature change must be less than the temperature difference between equipment and bus. Consequently, since the water loop transports sensible heat, higher flow rates (and higher weights) are incurred as the temperature difference decreases. A two-phase water heat transport system allows a higher bus temperature and potentially lighter weight system.

4.3.8.1 Two Phase Water Heat Exchanger and Line Sizing

The two phase heat exchanger weights were based on the analysis outlined in section 4.3.4.1. Because the water vapor density is low for the temperature range considered, the vapor pressure drop (in the vapor line between the equipment and interface heat exchanger) effect on vaporization (condensation) temperature was included in the analyses.

For the high temperature heat rejection system case the vapor line was fixed at an inside diameter of 2.25 inches and the liquid line at 0.5 inch inside diameter. These line sizes result in an overall head difference of about 1 inch, which is compatible with capillary pumping. The vapor line pressure drop produces a difference between vaporization temperature, at the equipment heat exchanger, and condensation temperature, at the interface heat exchanger, of 1.76°F. The heat exchangers were optimized as a function of

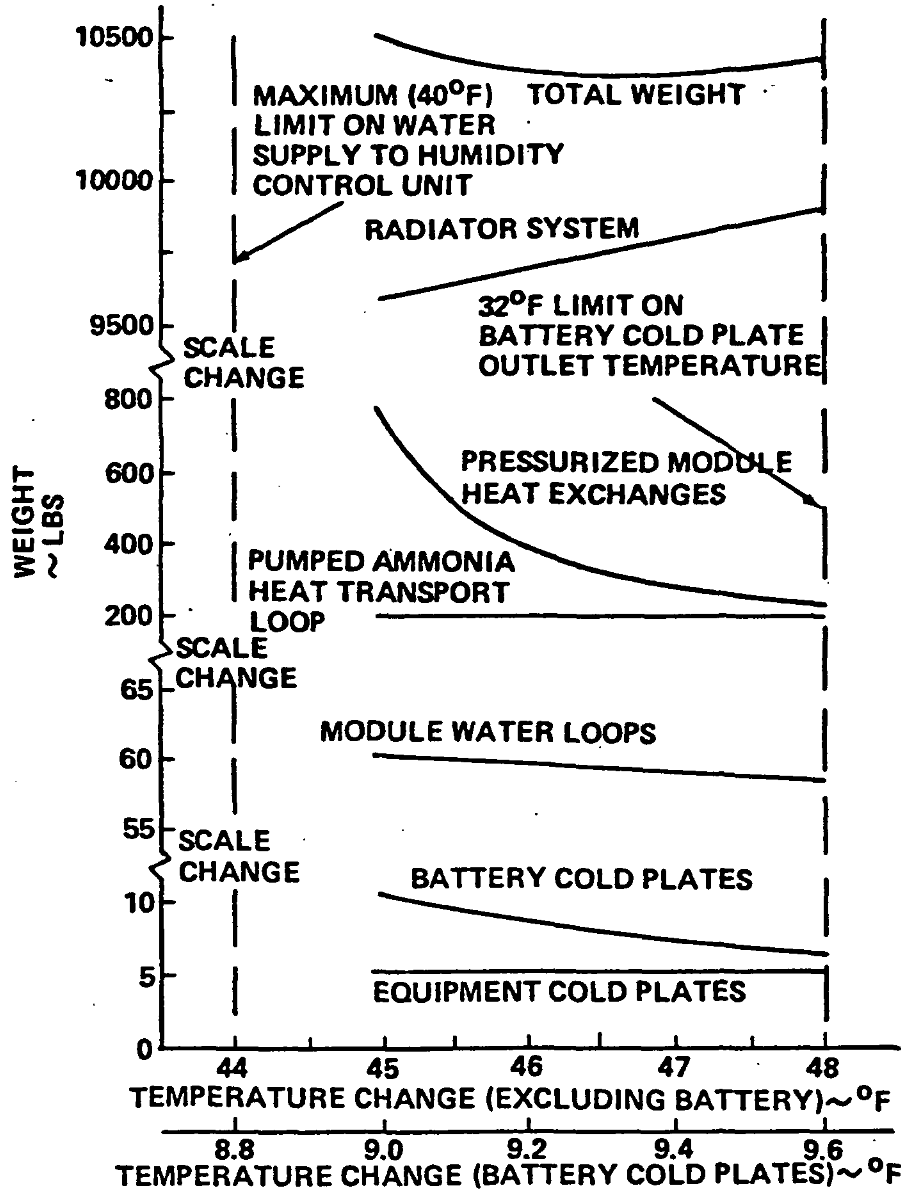


Figure 4.3-19 Pumped Liquid Loop (Ammonia with 80°F Radiator Inlet)

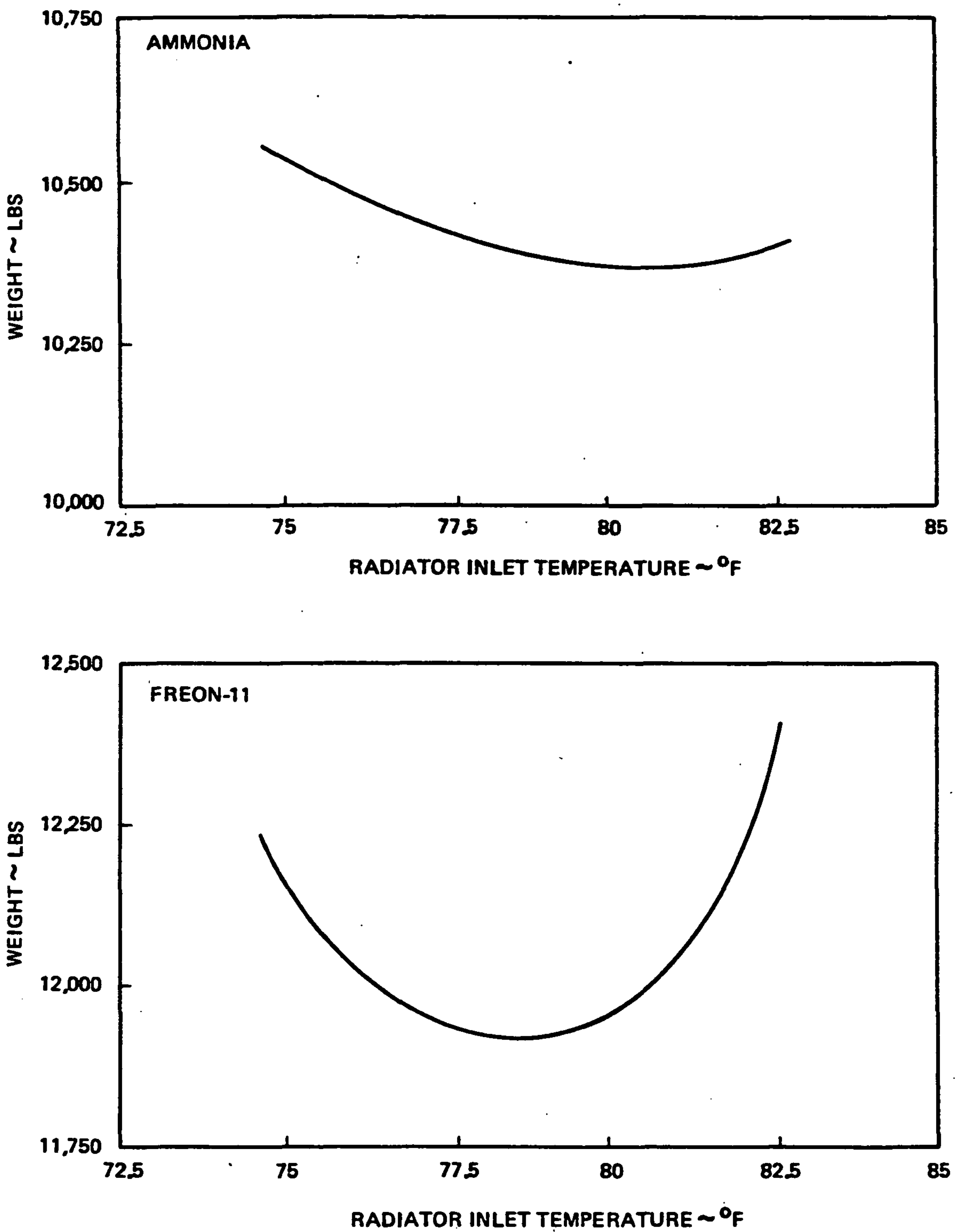


Figure 4.3-20 Optimized Total System Weight for Pumped Liquid Heat Transport System

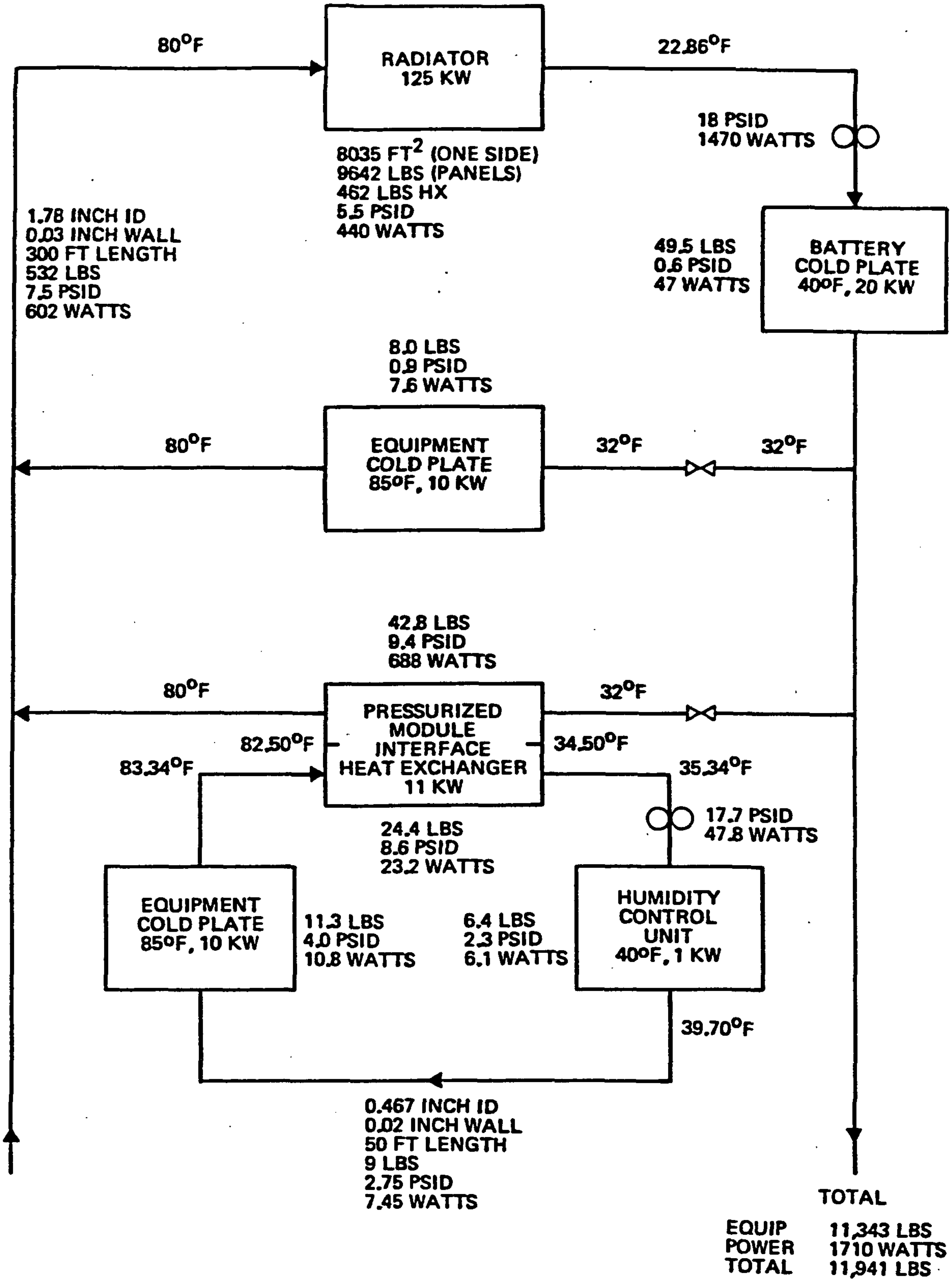


Figure 4.3-21 Pumped Liquid Freon-II System Schematic

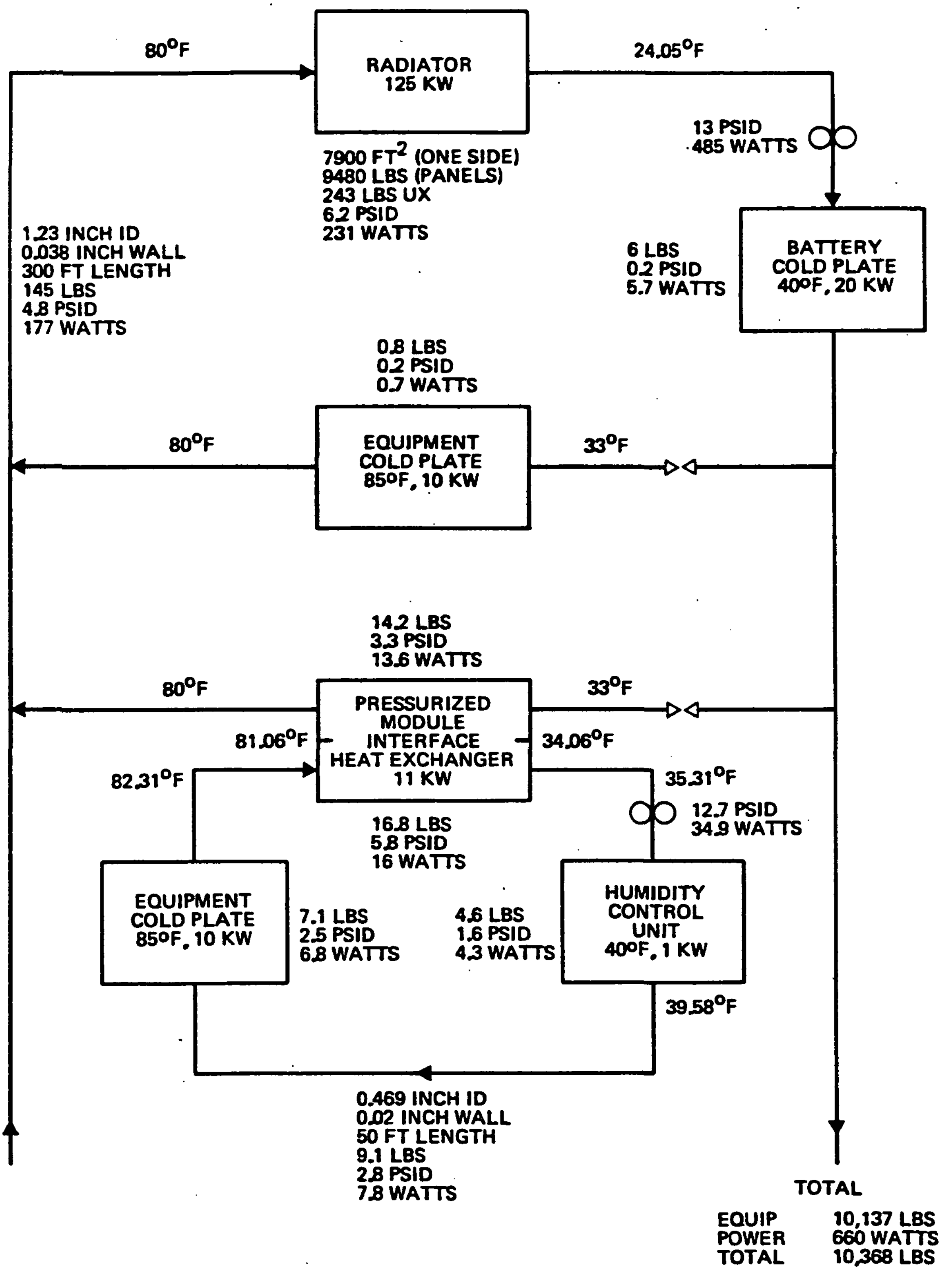


Figure 4.3-22 Pumped Liquid Ammonia System Schematic

equipment to bus temperature difference that included this fixed vaporization temperature difference.

The effect of pressure drop on vaporization temperature is more pronounced in the low temperature heat rejection case. In this case the vapor line size was optimized in conjunction with heat exchanger optimization to provide the lowest weight system for a given humidity control unit to bus temperature difference. The liquid line size was fixed at 0.25 inch O.D. with 0.02 inch wall.

4.3.8.2 Effect on System Weight

Figure 4.3-23 shows the effect of incorporation of two-phase water heat transport systems in the pressurized modules on the high temperature two-phase ammonia system element weights. The minimum total weight now occurs at a bus temperature of 79°F compared to the 70°F optimum for the system with pumped water loops. A detailed schematic showing the effects on the two-phase water system is shown in figure 4.3-24. The main bus sizes and weights remain unaffected. The equipment cold plate weights are increased due to the higher bus temperature. The radiator and pressurized module component weights are significantly reduced. The total system weight is 828 pounds less than that for the system with pumped water loops.

The effects on the low temperature heat rejection system are shown in figures 4.3-25 and 4.3-26. The optimum bus temperature for this case is 37.5°F compared to 36°F for the case with pumped water loops. As in the high temperature case the bus weight remains unaffected, the battery cold plate weight is increased and the other component weights are reduced. The total weight is 79 pounds less than that for the pumped water loop system.

4.3.9 Cost and Benefits Analysis

In the final report of the study completed in April of 1983 a cost and benefits assessment was given for developing thermal storage systems for both pumped liquid and two-phase heat transport concepts. The result indicated that those technology advancements were among the most desirable of the ones identified in that study. It was indicated in that study that development costs for the two-phase system would be 50% higher due to the complexity of:

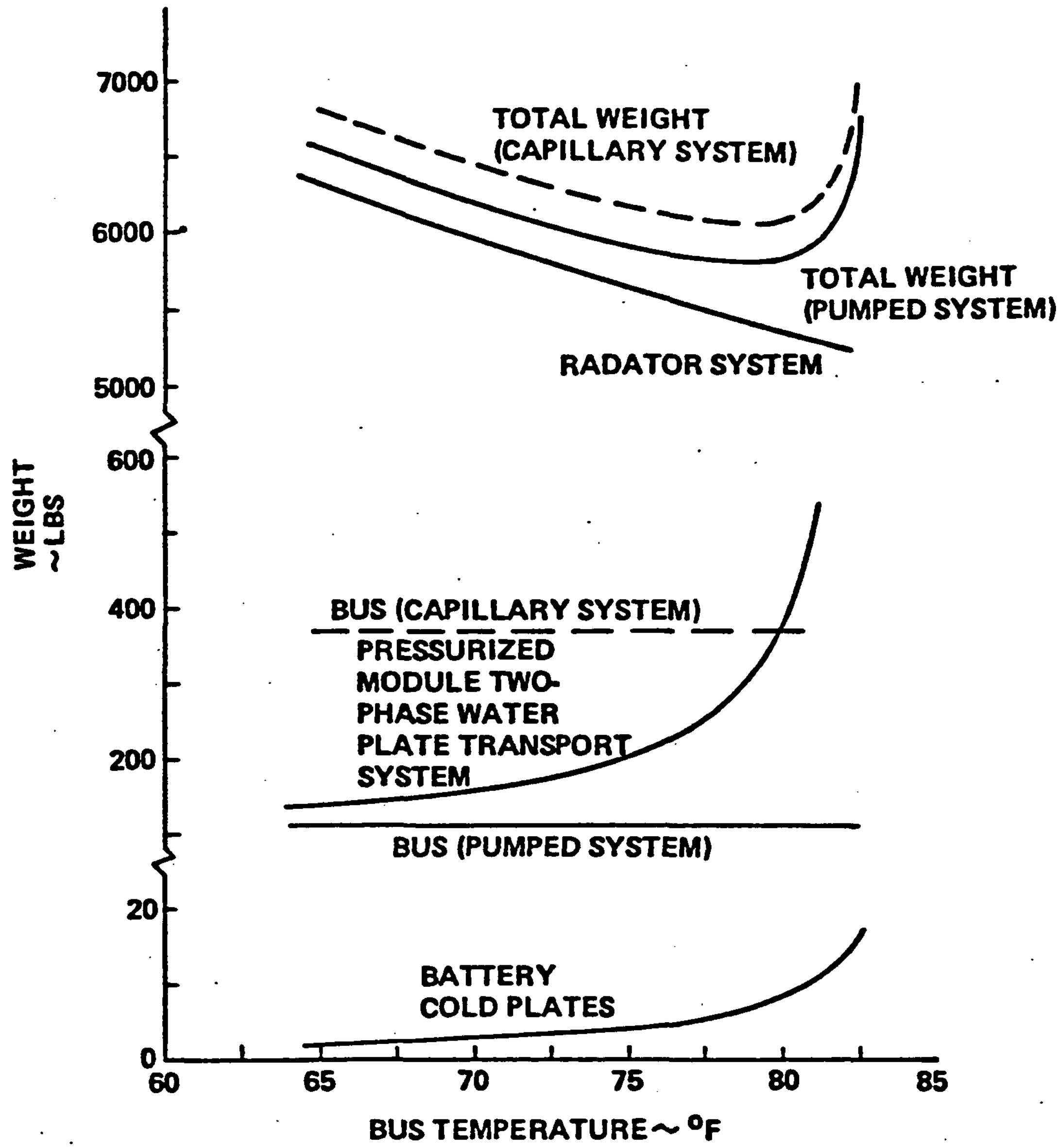


Figure 4.3-23 High Temperature Two-Phase Ammonia Bus with Two-Phase Water Loops

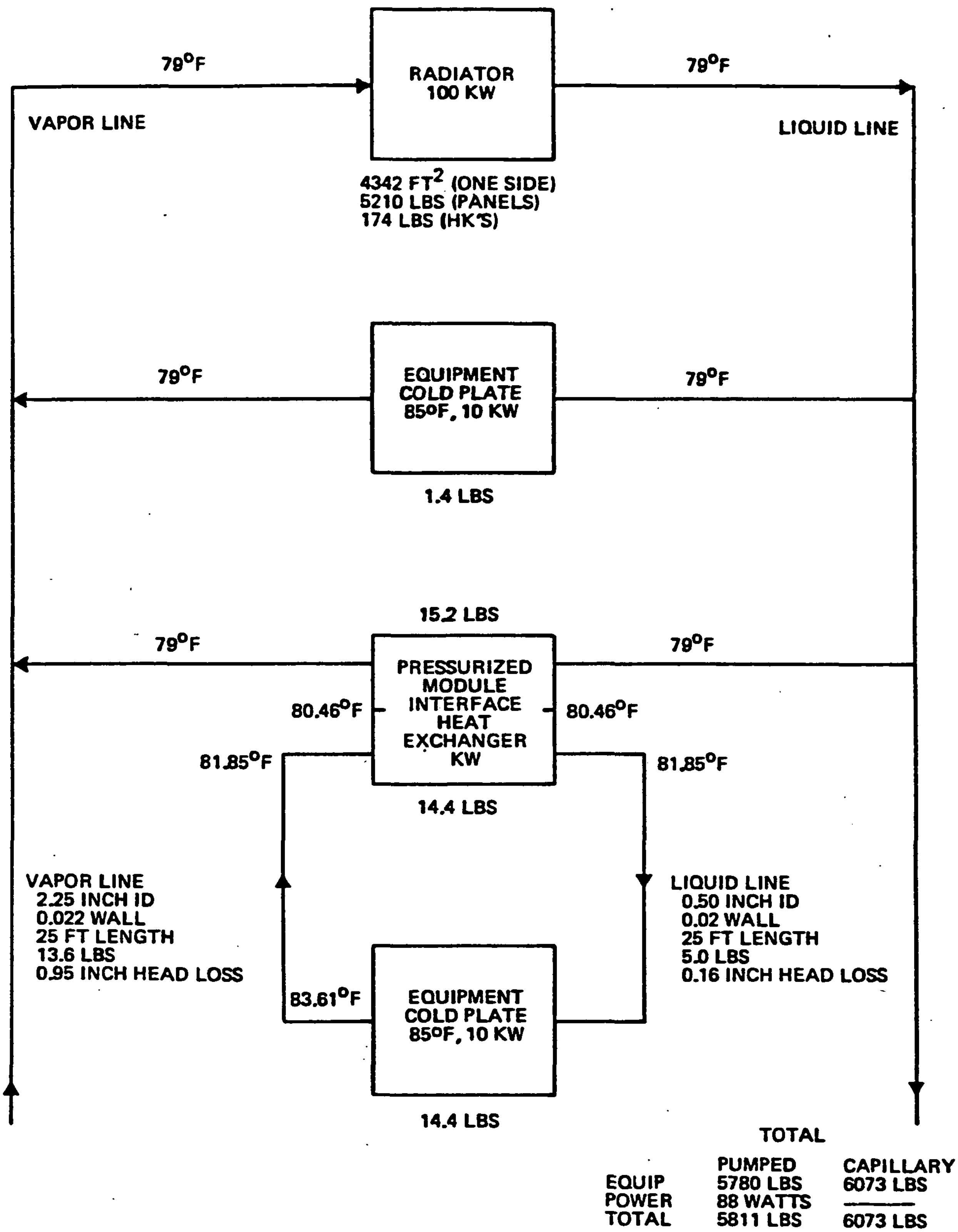


Figure 4.3-24 Effect of Two-Phase Water Heat Transport System on High Temperature Bus

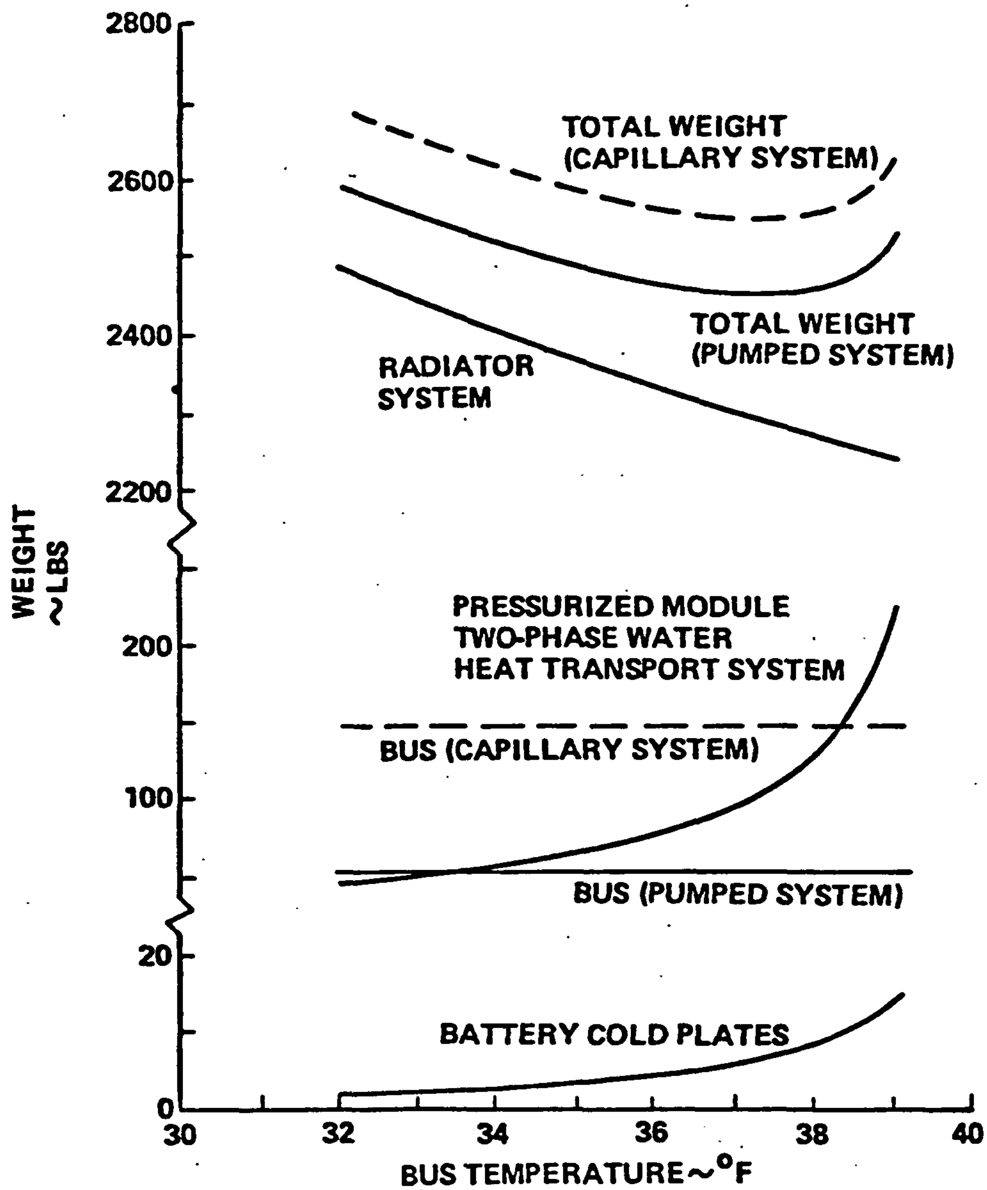
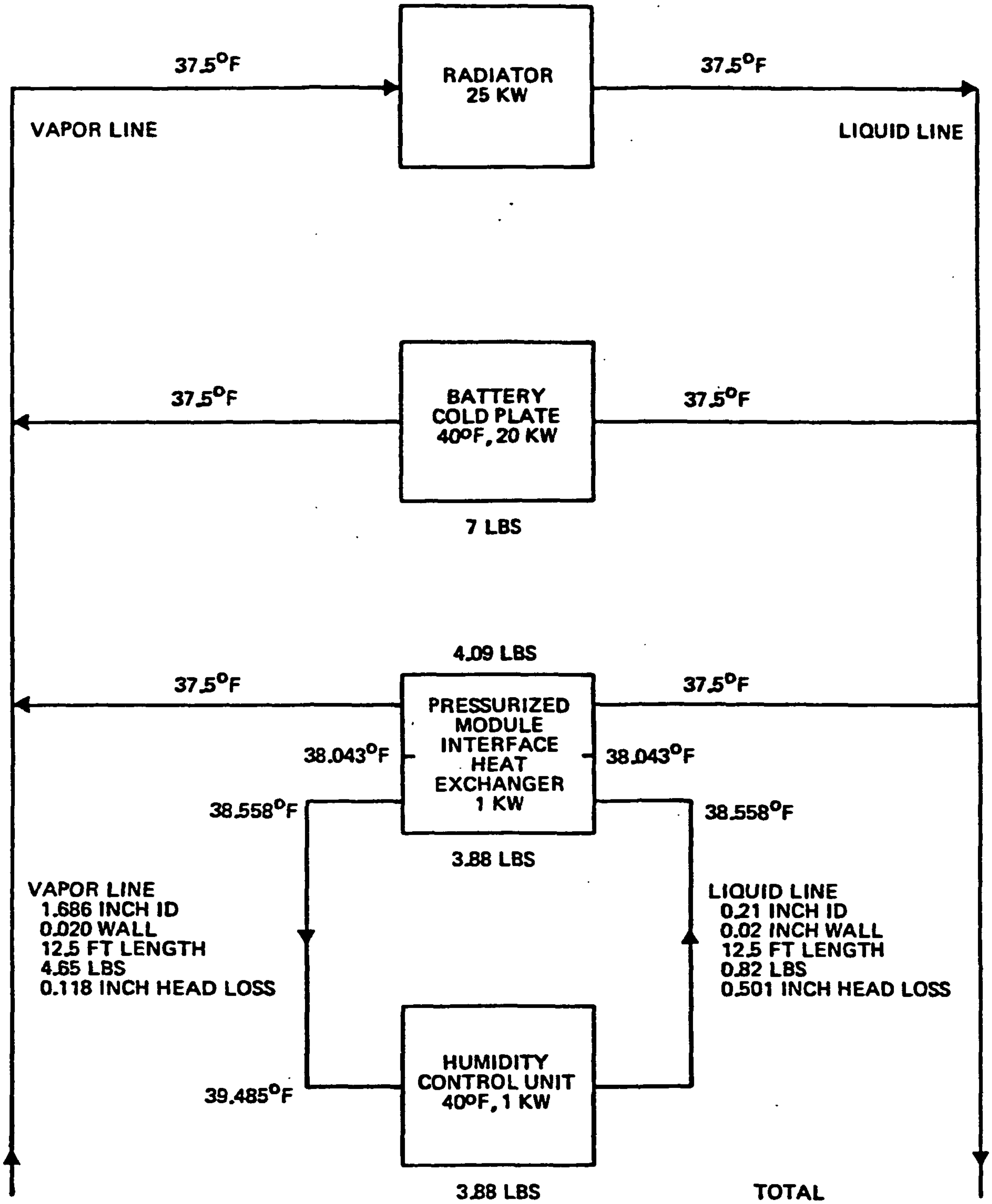


Figure 4.3-25 Low Temperature Two-Phase Ammonia Bus with Two-Phase Water Loops



	PUMPED	CAPILLARY
EQUIP	2416 LBS	2528 LBS
POWER	42 WATTS	
TOTAL	2431 LBS	2528 LBS

Figure 4.3-26 Effect of Two-Phase Water Heat Transport System on Low Temperature Bus

1. Phase change material packaging.
2. Thermal interface with the heat transport system.

In the current study a further assessment of the pumped liquid versus two-phase heat transport system was conducted. Two technologies were identified for advancement specifically to support the development of a two-phase system. These are—

1. Two-phase water thermal transport loops for inhabited environment.
2. Heat exchanger for liquids in nearly saturated state in zero gravity.

The quantifiable benefits of these advancements are that the two-phased system is less complex than the pumped liquid system; that the two-phased system weighs less than the pumped liquid system and that means lower cost to transport the system to orbit; and finally the area of the radiator is less for the two-phased system and that means the assembly labor costs will be lower.

The two systems compared are given by the pumped Freon-11 system of figure 4.3-21 and the pumped two-phased water heat transport system of figures 4.3-24 and 4.3-26.

The complexity factors were compared using the RCS PRICE modelling technique and the result came out $21.26M for the liquid and $16.08M for the two-phased that results in $5.18M in favor of the two-phased system.

The transportation costs were calculated using $718. per pound to orbit and the difference in system weights. This resulted in $2.66M in favor of the two-phased system. The assembly costs were based on $77,000 per 24-hr day for astronaut time and the assessment which was used in the last study of 8 labor hours to assemble 100 square feet of radiator. This resulted in a $475,000 saving for the two-phased system.

The cost of advancing the technologies involved has been estimated to be $0.8M for the heat exchanger program and $2.59M for advancing the two-phased water interior loop system (assuming use of shuttle test data for heat pipes rather than a complete independent flight test). Together these represent an expense for technology advancement for a two-phased heat transport system of $3.4M.

Using the above figures the cost over benefit ratio of advancing technologies to support the two-phased heat transport system is 0.41. This is based on the \$3.4M advancement cost divided by \$8.32M benefits.

4.4 SUMMARY OF RESULTS

The weights for the various heat transport systems, applied to the baseline space station, are summarized in table 4.4-1. The pumped two-phase ammonia system used in conjunction with two-phase water heat transport inside the pressurized modules is the lightest system. The corresponding capillary two-phase system is 359 pounds heavier. The pumped two-phase system with pumped water loops inside the modules is 907 pounds heavier. The pumped liquid ammonia system is heavier by 2,126 pounds and the pumped freon system is heavier by 3,699 pounds. The total radiator area required is: 6186 ft^2 for two-phase ammonia systems in conjunction with two-phase water loops; 6690 ft^2 for two-phase ammonia systems with pumped water loops; 7900 ft^2 for pumped liquid ammonia system; and, 8035 ft^2 for pumped freon system.

4.5 CONCLUSIONS

A pumped two-phase heat transport system provides approximately a 1000 lbm weight reduction and power and size reductions compared to a pumped liquid loop system. More importantly, the two-phase system offers greater flexibility in configuring the space station.

A capillary two-phase heat transport system offers the advantages of a pumped two-phase system with a relatively small weight increase. The capillary system does not need the pumps, valves and controls needed for the pumped two phase system. Consequently a capillary system is, in principle, a more reliable system.

For pressurized modules, a two-phase water heat transport system rather than liquid water system provides an additional weight savings when used with a two-phase main transport system. A capillary two phase water system could potentially increase reliability and reduce vibration and noise.

Alternative pumping concepts for the pumped two-phase system were considered briefly. One concept uses an osmotic pump in place of the baseline mechanical pump. This

Table 4.4-1 System Weight Comparison

	TRANSPORT LOOP	COLD PLATES	MANNED MODULE WATER LOOPS	HX's	RADIATOR	TOTAL WEIGHT
PUMPED LIQUID LOOP						
FREON II	742	119	59	762	10259	11941
AMMONIA	207	13	59	285	9804	10368
TWO-PHASE AMMONIA						
PUMPED						
HIGH TEMP	107	3	171	400	5958	6639
LOW TEMP	52	4	46	70	2338	2510
TOTAL	159	7	217	470	8296	9149
CAPILLARY						
HIGH TEMP	369	SAME AS PUMPED TWO-PHASE				6901
LOW TEMP	149					2607
TOTAL	518					9508
TWO-PHASE AMMONIA SYSTEM WITH TWO-PHASE WATER SYSTEM IN MANNED MODULES						
PUMPED						
HIGH TEMP	107	7	93	220	5384	5811
LOW TEMP	52	7	27	59	2286	2431
TOTAL	159	14	120	279	7670	8242
CAPILLARY						
HIGH TEMP	369	SAME AS ABOVE				6073
LOW TEMP	140					2528
TOTAL	518					8601

NOTE: 125 KW HEAT LOAD (100 KW AT 85°F; 20 KW BATTERY & 5 KW METABOLIC AT 40°F)
300 FT TOTAL TRANSPORT DISTANCE

concept provides pumping by osmotic pressure that causes solvent to flow through a semipermeable membrane into a solution which flows to the evaporator. This concept requires auxiliary mechanical pumps to keep the solution from being diluted next to the membrane. The weight, reliability, and performance deficiencies of this concept eliminates it from serious consideration as an alternate pumping scheme. The other concept considered was an ion drag pump that produces fluid flow by creating ions in a corona discharge. The ions are accelerated in an electric field and impart momentum to the fluid. This scheme has the advantage of pumping with no moving parts. However, the pumping efficiency is only about 10%, high voltages are required, transport fluid must be a dielectric, and the corona discharge may have degrading effects on the fluid and electrode.

4.6 RECOMMENDATIONS

The results of the study showed that the weight of a two-phase heat transport system is approximately 1200 lbm less than that of a comparable single-phase system of identical capacity. This 12% lower weight alone would probably to be sufficient justification for the selection of a two-phase system for the space station. The most compelling reasons for the choice of a two-phase transport system are (1) flexibility in locating heat loads and reconfiguring experiments, (2) modular growth of the station, and (3) stable temperature interface with cooling and heating loads over an inside range of operating conditions.

The two-phase system concept, however, has some inherent technical risks that will require expensive space flight testing to resolve. The developmental costs of the two-phase system would therefore be expected to be considerably greater than the cost of developing a single-phase system.

Additional information is needed before a sound decision can be made as to which thermal transport system should be selected for the initial space station. It is therefore recommended that a program be initiated to generate the necessary information to support the selection of a space station thermal transport system. A three-step program is envisioned. In the first step, system requirements would be established. These requirements would stem from the definition of (1) system loads such as experiments, equipment, etc. (2) planned space station evolutionary growth, and (3) space station mission planning.

Candidate single- and two-phase transport system would be designed and optimized in the record program step. These systems would be developed for a baseline station and mission drawn from the step one requirements definition study. Dollar cost benefits of each transport concept would be quantified for all important system attributes including:

1. Mass.
2. Size.
3. Flexibility and growth.
4. Reliability.
5. Maintainability.
6. Constructability.
7. Operation costs.

In the third step, detailed plans for transport system development would be prepared. Developmental costs would then be predicted and a cost and benefit analysis performed to identify the best thermal transport system concept.

Regardless of the final selection of the thermal transport system concept for the space station, the potential benefits of the two-phase systems warrant immediate technology development. Such developments are necessary to bring the level of technical maturity up to the point required for space station preliminary design. Because a pumped two-phase thermal bus system development program is currently in progress under NASA JSC contracts NAS9-16781 and NAS9-16782, it is recommended that emphasis should be placed on development of a two-phase transport loop suitable for thermal management within pressurized inhabited environments of the space station. The high-performance fluids (ammonia or freon) envisioned for use in the main thermal transport bus cannot be used in inhabited areas due to their toxicity. Water would be the first choice for the working fluid in the internal transport loop. A two-phase design would provide the flexibility, modular growth capability, and isothermal interface characteristics desired for the overall thermal management system. Both mechanically pumped and capillary pumped loops should be investigated. Special emphasis should be placed on developing pump and heat exchanger technology that would benefit both the main bus and internal transport loop concepts. In addition, capillary pumping for the main thermal transport system should be investigated because of the potential for increased reliability and reduced power, noise, and vibration by eliminating mechanical pumps. Volume III provides preliminary plans for the accomplishment of these advances.

5.0 INTEGRATION OF AUTOMATED HOUSEKEEPING

This section presents the results of the study conducted to characterize a system for integrating the automation of several housekeeping subsystems on an inhabited space station. This integration system will be a step toward meeting the automomy/automation philosophy for the space station which has been defined by the Concept Development Group (see table 5.1-1).

5.1 INTRODUCTION

In the Advanced Platform Sytems Technology Study completed in early 1983, the cost versus benefits of integrating the automation of several utilities producing subsystems on a space station was assessed. The results of this assessment gave indication that the function of providing this integration could produce savings to the space station over a 10-year life of $184M. The same study indicated that a large part of the cost of such a system would be the software development and the probable use of expert systems technology. These cost figures were assessed as being about $9M. Because the system had not been described at a detailed level and because the cost/benefits were impressive, it was decided to conduct the current study to take a more detailed look at the functions of such a controller. The current study also produced a reassessment of the cost and benefits of the system and generated a more definitive identification of the applicability of expert systems to the process.

The following paragraphs report on the approach, results, conclusions, and recommendations resulting from this characterization study and also provide a technical discussion of the study elements.

5.2 APPROACH

The objective of this study was to obtain a characterization of the Integrating Management Controller to allow a better understanding of the benefits possible and the technology needed for implementing such a controller so that it will provide reliable, real-time management of the separate housekeeping controllers on a space station. To accomplish this objective the results of the initial study were extended by a more detailed modeling of how a management type controller might be employed. The model was then examined to identify options in the implementation which better defined the benefits to be obtained from the integration process.

Table 5.1-1

Space Station Autonomy/Automation Philosophy

Subsystem/system monitoring and control will be performed on board.
Systems monitoring and control will be automated.
Fault detection and isolation will be an automated function for all subsystems.
Redundancy management including reconfiguration will be performed automatically on board.
Reverification of systems/subsystems elements will be performed automatically on board.
Operations planning and scheduling will be performed on board.
The degree of automation will increase as the space station grows and technology becomes available.
Collection and analysis of trend data will be automated.
The space station platform shall have the same degree of automation on board as the manned base.

The following paragraphs indicate in some detail the approach steps used in this study.

5.2.1 Update the Housekeeping Functions List

In performance of this subtask a system analysis was conducted to update the following list of functions to be performed by each of the three automatic housekeeping subsystem controllers:

Table 5.2-1
Functions For Housekeeping Controllers

Electrical Power	Thermal	Life Support
Control voltage at power user outlets.	Control temperature to set points within cabins.	Control oxygen and nitrogen supplied to cabin.
Control power levels at power user outlets.	Control temperature at heat exchangers for specific equipment items.	Control contamination level in cabin air.
Switch sources based on sensed status of sources	Control humidity of cabin atmosphere.	Control quality of potable and wash water. Removal of CO_2 from cabin air.

The above list indicates the starting point on independent control functions within each of the three housekeeping subsystems on the space station considered in this study. These functions are those which relate to maintaining environment on the space station for the crew and for the mission peculiar equipment. In this subtask the list was expanded for models of the three subsystems to the level of detail where the control parameters would be sensed.

To accomplish this expansion, a review was conducted of thermal control automation progress reports, of briefing material for power system automation (MCR-82-631 dated 2-9-83), and of Space Station Environmental Control and Life Support System—Preliminary Concept Design Report (JSC-17727). This review extracted descriptive information about those subsystems and their automation that was used to identify the following:

1. Functions performed by automation of the subsystems.
2. Quantities which would need to be sensed in order to perform the automation.

These items were then listed and are presented as tables 5.3-1, 5.3-2, and 5.3-3 of this final report. Use of this information was made in the next step of the study as described in the next paragraph.

5.2.2 Define Functions to Integrate the Automation of the Housekeeping System

A systems analysis was performed to develop a concept for integrating the control of the three housekeeping functions and to identify the control parameters involved. The analysis process used the control functions list developed by the review described above and identified where the items on the list had relationship to the control of another subsystem. Outside events, which can effect control of the housekeeping subsystems, were then identified. Using these lists of functions and data, the functional concepts for the integrating controller were developed. Figure 5.3-2 shows the relationships considered and lists the outside events considered.

Based on the interactions identified by the above process functions were identified for the integrating controller. Functional block diagrams were then developed along with functional descriptions of each of those identified. These functional block diagrams and descriptions are also presented under section 5.3 of this report.

5.2.3 Identify Integration Functional Scenarios

Because various mode shifts would be selected and implemented by an integrating controller, it was necessary to identify the mode shifts and to assess the sequencing of the action. The scenarios for operation of an integrating controller were conceptualized in this subtask by a systems analysis approach. The scenarios were developed from the nominal and functional sequences listed below.

1. Management of start-up modes.
2. Management of load sharing for electrical power and thermal control according to astronaut usage patterns, sunlight/darkside passages, and special events such as EVA or module reconfiguraiton activities.
3. Management of emergency and redundant path modes.
4. Management of material transfer and shutdown modes.

Table 5.3-1

Electrical Power Subsystem Automation

Functions

- Control solar array orientation
- Control of solar array selection - segment selections
- Regulation of solar array output voltage - shunt regulation
- Control of battery charge-discharge processes
- Battery selections - cell selections
- Load sharing control of regulators
- Shunting for under use control
- Redundancy Management within the electrical power system

Sensed Quantities

- Solar array temperatures
- Solar array positions
- Solar array voltages by sections of the array
- Battery cell voltages
- Battery cell temperatures
- Battery cell pressures
- Battery charge voltage
- dc/dc converter line voltage
- Transformer coupled converter output voltage
- Series resonant inverter (dc/ac) output voltage
- Series resonant inverter fuse status
- Magnetic latching relay position
- Cable temperature

Table 5.3-2

Life Support Subsystem Automation

O_2 Generation

Functions

- Control of the flow of water to the electrolysis units
  - Valve operation
  - Pump operation
- Control of electrolysis current
- Control of the flow of H_2 away from the unit
  - Valve operation
- Control of the flow of water away from the unit
  - Valve operation
  - Pump operation
- Control of the flow of oxygen away from the unit
  - Valve operation
- Redundancy management within the O_2 generator
  - Detection of failure
    - Abnormal values of several quantities
  - Selection of redundant elements: generators/pumps/valves

Sensed Quantities

- Partial pressure of cabin O_2
- Flow rate of input water
- Pressure of H_2 at output
- Flow rate of water at output
- Pressure of O_2 in storage at output
- Selected set point condition
- Status of valves, pumps, generators and storage units

Table 5.3-2 (Continued)

Life Support Subsystem Automation

N_2 Supply

Functions

- Control of the flow of N_2 from storage
  - Valve operation
- Redundancy management functions within the N_2 supply
  - Detection of failures
    - Abnormal values of several quantities
  - Selection of redundant valves

Sensed Quantities

- Cabin pressure
- Pressure of N_2 storage tanks
- Selected set point
- Status of valves and storage tanks

CO_2 Removal

Functions

- Position of by-pass valves to control air flow to beds
- Position of by-pass valves to isolate beds for desorption from the cabin
- Control of electric heaters to create steam to flow through beds being desorbed
- Control of valves to direct CO_2 to the reduction system from the beds being desorbed
- Control of valves to provide hygenic water for steam into desorbed beds
- Redundancy management
  - Detection of abnormal sensed values
  - Selection of redundant elements: fans, by-pass valves, beds, and steam generators

Table 5.3-2 (Continued)

Life Support Subsystem Automation

Sensed Quantities

- Partial pressure of cabin CO_2
- Flow rate of water at input to steam generator
- Pressure of CO_2 in accumulator at output
- Temperature of steam in steam generator
- Flow rates at desorbed bed
- Status of beds being used for absorption and being desorbed
- Status of valves and fans
- Selected set point

CO_2 Reduction

Functions

- Mixing of H_2 and CO_2
- Flow of mixed CO_2 and H_2 through filter to the reduction unit
- Pump and valve control for water accumulator at reduction unit output
- Redundance management within the CO_2 reduction unit
  - Selection of redundant elements: reduction unit, valves, and accumulator
  - Failure detection based on abnormal sensed values
- Cooling for unit

Sensed Quantities

- Flow and pressure of gases at input
- Temperature of unit
- Flow and pressure of gases at output of unit
- Flow of water to accumulator
- Capacity filled with water in accumulator
- Flow of water out of accumulators
- Status of valves and accumulators

Table 5.3-2 (Continued)

Life Support Subsystem Automation

Trace Contamination Control (TCC)

Functions

- o By-pass valves to control air flow through beds
- o Annunciation of below normal bed status
- o Control of power to electric heaters
- o Redundancy management within the trace contamination control system
  - o Failure detection based on abnormal sensed values
  - o Selection of redundant elements: alternate fans, paths through beds, and oxidizer

Sensed Quantities

- o Level of contamination
- o Temperature of oxidizer
- o Flow through units
- o Status of fans, valves, oxidizer heater and beds
- o Selected set point

Potable Water Process

Functions

- o Control of water flow to post-treat
  - o valves
  - o pump
- o Control of cycling in post-treat and Water Quality Monitor (WQM)
  - o valves
  - o pumps
  - o WQM processes
- o Control of flow to selected storage tank
- o Control of iodine addition in storage tank testing process
- o Control of overflow to hygienic water
- o Control of water heater
- o Control of use flow out of storage tanks

Table 5.3-2 (Continued)

Life Support Subsystem Automation

Functions (Cont)

- o Redundancy management with the potable water processor system
  - o Failure detect
  - o Seclection of redundant elements: accumulators, water quality monitors, (WQM), tanks, valves, and beds

Sensed Quantities

- o Capacity filled in accumulators
- o Measured contaminants in WQM
- o Capacity filled in storage, test, use tanks
- o Iodine level in storage tank test processing
- o Post treat valve and bed status
- o Water temperatures in system
- o Storage tank valve status
- o Water flow rates in system

Hygenic Water Process

Functions

- o Control of pre-treat pumping
- o Control of pre-treat biopal VRG 20 addition
- o Control of pumping and valving into the vapor-compression distillation (VCD) unit
- o Control of compression in VCD
- o Control of heating in VCD
- o Control of conductivity testing of VCD condensate and valving for output
- o Control of post-treat valving and pumping
- o Control of WQM processes
- o Control of flow to fill-use tanks
- o Control of flow out of fill-use tank

Table 5.3-2 (Continued)

Life Support Subsystem Automation

Functions (Cont)

- o Redundancy management within the hygenic water processor system
  - o Failure detect
  - o Select redundant elements: WQM, VCD, valves, fill tanks, pumps and heaters

Sensed Quantities

- o PH level in pre-treat
- o Flows in pre-treat
- o Waste holding tank capacity filled
- o Valve status indicators
- o Waste tank capacity filled
- o Sludge tank capacity filled
- o Flows into VCD
- o Pressure in VCD
- o Temperature in VCD
- o Conductivity of VCD condensate
- o Flow of condensate from VCD
- o Measured contaminants in WQM
- o Post treat valve and bed status
- o Flow rates in post treat and storage
- o Storage tank valve status
- o Capacity filled in storage tanks
- o Capacity filled in accumulators in system

Wash Water Process

Functions

- o Control of pumping to work holding tank
- o Control of pumping and valving to hyper-filtration process

Table 5.3-2 (Continued)

Life Support Subsystem Automation

Functions (Cont)

- o Control of heating in hyper-filtration process
- o Control of valving and pumping from the hyper-filtration process
- o Control of the addition of sodium hypochlorite in post-treat
- o Control of the addition of iodine in post-treat
- o Control of pumping and valving for post-treat
- o Control of pumping and valving for storage of wash water
- o Redundancy management within the wash water processor system
  - o Failure detection
  - o Selection of redundant elements: pumps, valves, hyper-filtration units, and tanks

Sensed Quantities

- o Flows to and from holding tank
- o Flows to and from the hyper-filtration processor
- o Temperature of hyper-filtration processor
- o Capacity filled in holding tank
- o Capacity filled in hyper-filtration process
- o Measured contaminants in WQM
- o Post-treat valve and bed status
- o Flows for post-treat and to storage
- o Storage tank valve status
- o Capacity filled in storage tanks
- o Quantity of iodine and sodium hypochlorite available for use
- o Capacity filled in sludge tank

Table 5.3-3

Thermal Control Automation

Functions

- Control of cabin air flow through heaters
- Control of heaters
- Control of heat exchanger condensate flow to separators
- Control of water flow out of separators
- Control of positions of steerable radiators or selections of selectable radiators
- Control of coolant flow - valve positions or pump speeds
- Redundancy management within the thermal control system
  - Sensed failures from abnormal sensor values
  - Selection of redundant elements: fans, heaters, heat exchanges, separators, pumps, and valves

Sensed Quantities

- Temperature of cabin air
- Humidity of cabin air
- Input air flow to heater
- Condensate flow at heat exchanger
- Water flow out of separators
- Air flow out of separators
- Heater temperature
- Set point status
- Equipment status
- Position and rate information for steerable radiator servos
- Valve positions
- Pump speeds

5. Management of maintenance scheduling and interaction with normal or emergency modes.

The subtask was conducted at a conceptual level and the results indicated that the scenarios simply reinforced the functional descriptions already being developed under the previous subtasks. In addition it was determined that scenarios of significant detail would require a rather complete description of space station configurations, missions and operations. In the absence of such, the scenarios developed were general in nature. Tables of section 5.3.4.1 give the scenarios that were developed.

5.2.4 Identify Hardware and Software Elements of Integrating Controller

A systems analysis was conducted in cooperation with data management specialists to identify hardware and software elements of a concept for an integrating controller for automated housekeeping functions and to isolate technologies to be considered for advancement in order to implement the concepts. The use of artificial intelligence in the form of expert systems was explored to implement the flexibility and tolerance for change needed in this integrating controller.

The following questions were poised for the Data Management technical specialists on artificial intelligence:

1. Does this concept appear to need expert system implementation?
2. If it doesn't need it, would it benefit from it?
3. Describe how expert systems could be used in implementing this concept.
4. How many rules would be used in your estimation to implement the concept?
5. How much of the implementation would be on space station computers and how much would be in a ground installation?
6. What would be the characteristics of a space and ground computer system? Memory? Thru put rate? Anything else?
7. Describe the magnitude of development effort needed to achieve an expert system of the type needed for this concept; $ needed; years needed.

The answers received are given in section 5.3.6 of this report. In addition, figure 5.3-10 gives an initial cut on how the processing for an integrating controller might be grouped functionally in hardware systems both on board the space station and on the ground.

5.2.5 Compare Trade Study Results

The implementation options and system characterizations were analyzed to compare the benefits associated with the several functions identified for the integrating controller. This benefits comparison was based on the following considerations:

1. What is the extent of use of the function during space station operations?
2. Is an interactive mode using the function desirable or should it be fully automated?
3. Is the function essential for safety?
4. What is the extent of deterministic problem solving?
5. Does use of the function appear to increase with mission experience?

Section 5.3.7 gives the tabulation of this comparison and gives the resulting ranking of the benefits of implementing technologies for these functions.

Assessments of benefits of options for trade in areas architecture, on board versus ground processing, and human interaction versus fully automatic were also made. These assessments are also reported in section 5.3.7.

Finally a review of the cost and benefits ratio for expert system technology developed in the Advanced Platform Systems Technology Study was conducted and is reported in section 5.3.8.

5.2.6 Identify Technologies for Advancement

This subtask produced specific recommendations on the expert systems technologies advancement to support the development of an integrating controller for a space station. These technologies were identified at the level of specific procedures for advancement and this is discussed in section 5.3.9.

5.3 TECHNICAL DISCUSSION

This section presents in a detailed discussion of the study outputs along with the associated data and conceptual illustrations. The output discussion given by the following paragraphs are structured according to the sequence of the approach subtasks.

5.3.1 Automated Housekeeping Functions

The automation of three subsystems on an inhabited space station was investigated to identify the functions to be performed and the sensing that would be needed. The three subsystems were electrical power, life support, and thermal management and the automation being considered through this subtask is that which would be used internal to each of these subsystems in order that they can perform their functions automatically. The integration of these automated systems deals with interactions between them, with outside factors that affect them all or with trends that involve more than one subsystem.

The electrical power and thermal subsystem automations are fairly well understood and are also the subjects of separate NASA study contracts. For those reasons we used reports on the subjects to identify automation elements and these reports were: (1) MCR 82-631 "Power subsystem automation study" Briefing for program review and (2) Rockwell Monthly Progress Reports - NAS9-16782 "High Efficiency Automated Thermal Control System Program".

The life support subsystem on the other hand is in a conceptual state and the extent of expendable resupply versus onboard regeneration and the amount of automation that is practical are still unresolved issues. At present the life support concepts are being developed and the components are operated separately but not as an overall system. Figure 5.3-1 is an overall system concept which is reported in JSC-17727, "Space Station Environmental Control and Life Support System Preliminary Conceptual Design" DOC CSD-SS-059, dated 9/82. This concept was used to facilitate our identification of life support automation functions, but it is only one of several concepts and will undoubtably by modified before the space station baseline is established.

Referring to figure 5.3-1, the function of the system can be separated into:

1. Oxygen generation.
2. Nitrogen supply.
3. Carbon dioxide removal.
4. Carbon dioxide reduction.
5. Trace contamination control.
6. Potable water processing.
7. Hygenic water processing.
8. Wash water processing.

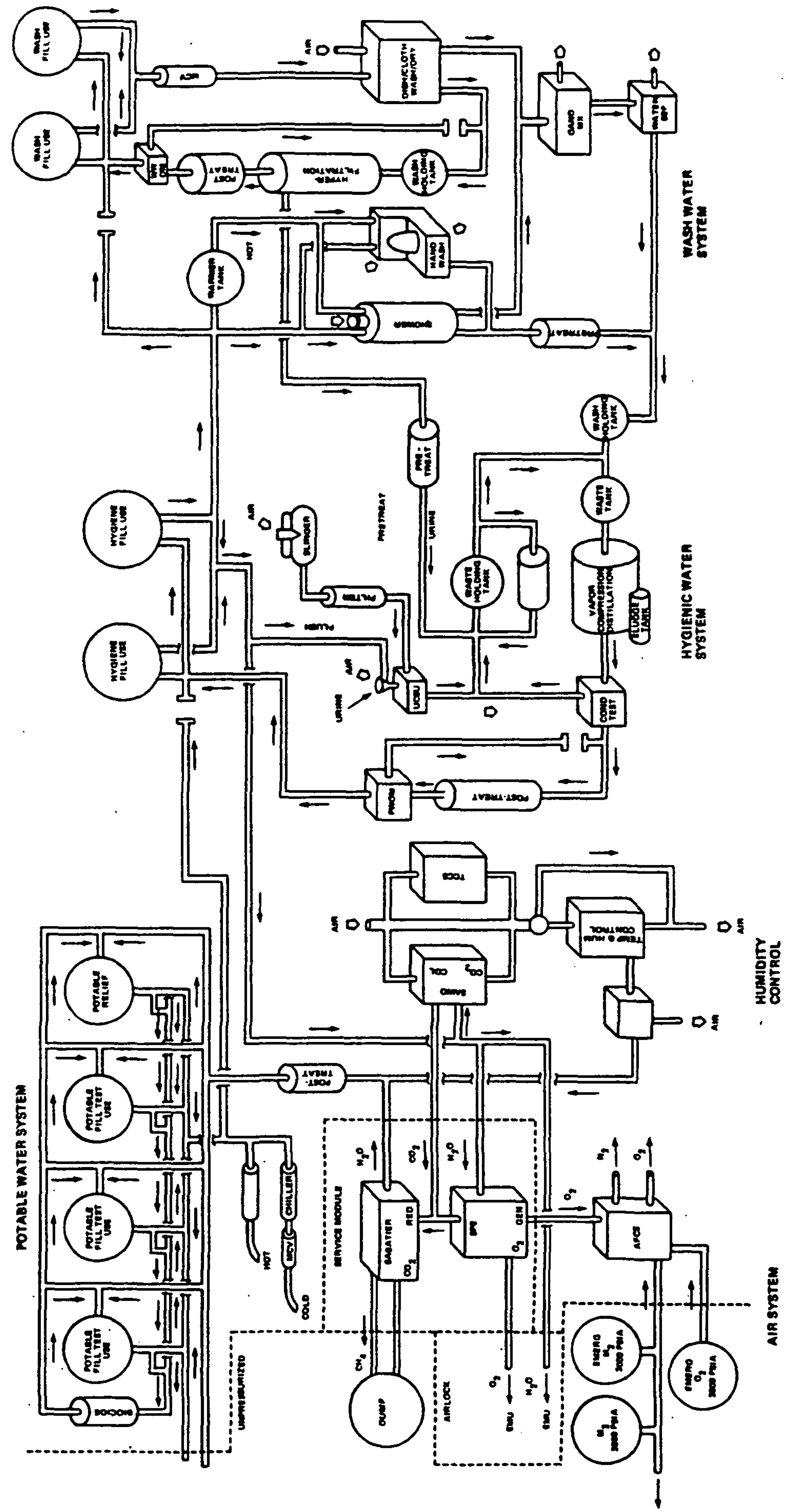


Figure 5.3-1 Schematic for Space Station Life Support Subsystem

These along with the cabin temperature and humidity control supported by the thermal management system are to provide the life supporting environment inside an inhabited space station in a regenerative sense. The automation functions and sensing for life support are identified in our study for each of these categories. Tables 5.3-1 through 5.3-3 give the results of analysis conducted of these subsystem concepts and lists the functions and sensed quantities for the automations identified.

The functions and sensed quantities in these tables were then used to construct an interface tabulation (see fig. 5.3-2) to identify when interactions between the automated subsystems could exist and where outside events could influence the overall operation. These identifications lead to the definition of functions for the integrating controller.

5.3.2 Integrating Controller Functions

The integrating controller is a concept that is intended to provide management level control of automated utilities subsystems on a manned space station. Initially this controller would be largely an advisory service for the astronauts. As such, it would tend to replace the advisory service which has been provided by mission control with a more autonomous interactive system that the astronauts can use on board. Because there will be actions that will be repetitive and bothersome to the astronauts it is a worthy goal to seek a fully automatic integrating controller for some functions.

This final report section gives some detail on the identification of functions to be performed by such an integrating controller. Based on the interactions shown by figure 5.3-2, it is clear that the three subsystems affect each other significantly and that there are outside factors that affect them all. The functions performed by an integrating controller would then deal with those interactions. Inspection of these indicate the following:

1. Electrical power load management is needed because both thermal and life support are heavy power users and reduction of their usage to balance loads needs to consider their interacting functions.

2. Materials transfer management is needed because outside factors affect the location of needs as well as the location of the availability of life support materials around the space station. In many cases transfers need to be considered against

FIGURE 5.3-2

TABULATION OF INTERFACES BETWEEN HOUSEKEEPING FUNCTIONS

INTERFACE BETWEEN ELECTRICAL AND THERMAL

- Battery cell temperatures
- Cable temperature
- Control of heaters (power usage)
- Shunting of power (generates thermal load)

INTERFACE BETWEEN ELECTRICAL AND LIFE SUPPORT

- Control of electrolysis current (power usage)
- Control of electric heaters to create steam to flow through beds being desorbed (power usage)
- Control of power to Trace Contamination Control Heaters (power usage)
- Control of heating in VCD (power usage)
- Control of heating in hyper-filtration process (power usage)
- Control of water heaters (power usage)

INTERFACE BETWEEN THERMAL AND LIFE SUPPORT

- Temperature of cabin air } air to life support
- Humidity of cabin air
- Water flow out of separators (water to life support)
- Air flow out of separators (air to life support)

OUTSIDE FACTORS WHICH EFFECT HOUSEKEEPING

- Lightside/Darkside
  - Electrical power solar arrays
  - Thermal radiators
  - Outside lighting
  - EVA constraint
- Crew size and level of activity
  - Life support load
  - Load on electrical power
  - Energy input to thermal
  - Moisture input to thermal
  - Distribution of life support materials, power loads, and thermal loads
- Compliment of Experiments
  - Load on electrical power
  - Load on life support materials
  - Constraint on dumping of waste
  - Thermal/humidity input
  - Distribution of life support materials, power loads, and thermal loads
- Shuttle Docked or Away
  - Air mixing between shuttle and station
  - Possible extra crew
  - Possible power sharing considerations
  - Possible thermal sharing considerations
- EVA or not
  - Extra load on life support before and after
  - Less load during
- Maintenance
  - System shutdowns while need for functions continues
  - Effect of maintenance on variations in performance of systems
  - Effect of maintenance on crew activity - EVA

scheduled events and against dumping constraints as well as impacts on power and thermal loading.

3. Intersubsystem failure isolation is needed because failure diagnosis outside of subsystem boundaries will have to be conducted in order to trace the cause through the interacting functions, e.g. an apparent failure of the separator in the thermal/humidity control system could be caused by an actual failure in the Water Quality Monitor (WQM) in the life support that is producing a backup into the accumulator receiving the condensate from the separators. In this case failure isolation within a subsystem would not be sufficient to find the problem.

4. Intersubsystem redundant path selection is needed because selection of redundant paths in response to failures or maintenance shutdown will have to consider the impact on interacting subsystems.

5. Maintenance schedule management is an integrated function since changes to the timing of maintenance actions for one subsystem can have affects on the operation and maintenance of other subsystems. This is because maintenance may cause temporary shutdowns and may result in changes in performance of the maintained subsystem that affect others.

6. Startup integration is needed to control the interdependent sequencing of bringing subsystems on line so that outputs are available before the need is created.

The following paragraphs give a more detailed description of each of these functions.

5.3.3 Functional Descriptions

The integrating controller described here is an overall management controller that processes data and commands functions that effect the automation of the following space station utilities producing subystems: electrical power, life support, and thermal control. It is assumed that each of these subsystems is automatically controlled within itself to track references in the presence of disturbances that effect the controller variables. The integrating controller then will basically change the references to these automatic controllers or change the configuration of the automatic controllers or of the subsystems being controlled in an orchestrated or integrated manner. Figure 5.3-3 shows

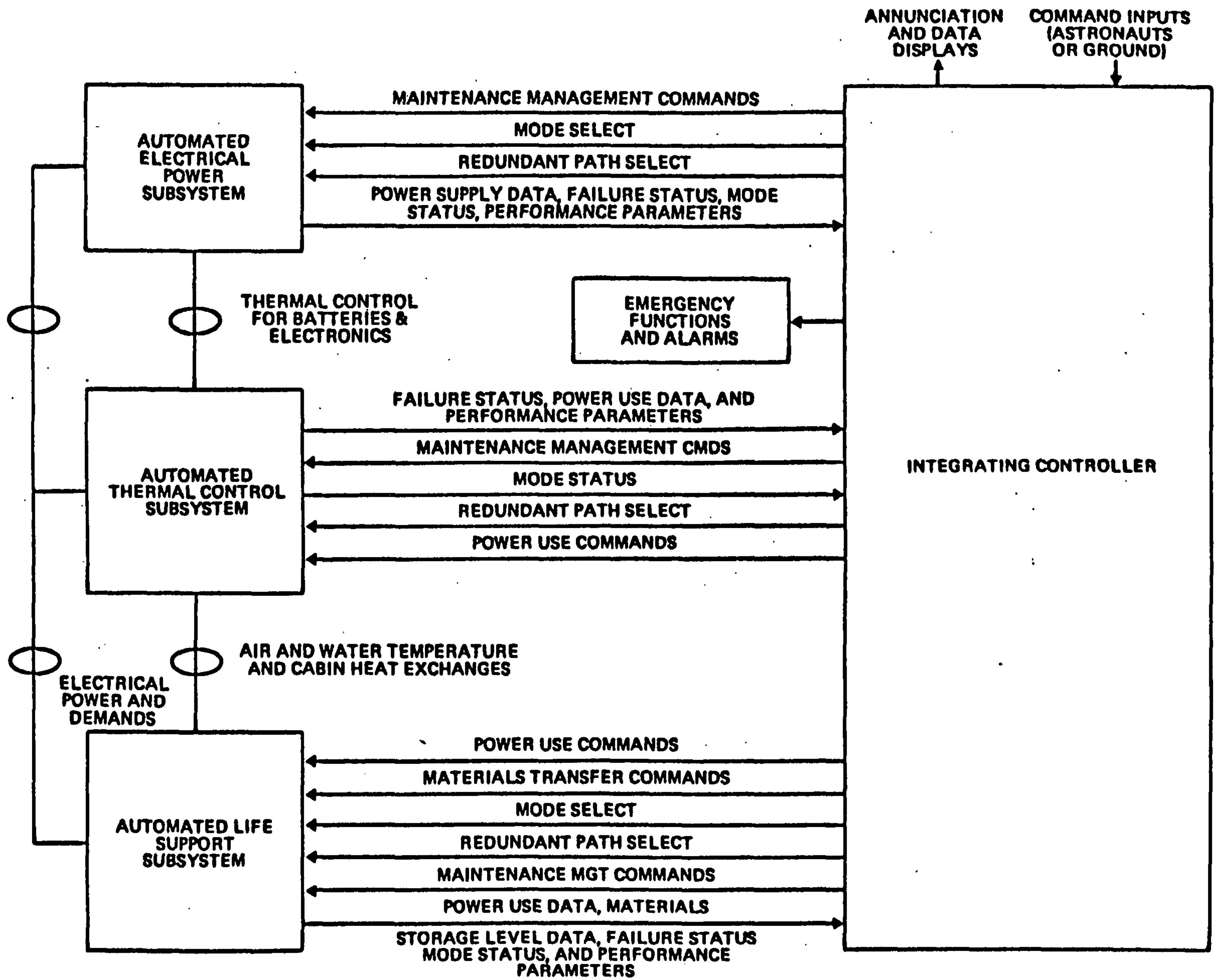


Figure 5.3-3. Interfaces Between an Integrating Controller and Automated Housekeeping Subsystems

the overall relationship of the integrating controller to the separate automated subsystems.

The functional goal of the integrating controller is to manage the interactions between the separate automated housekeeping subsystems so that the overall system may continue to operate through events or conditions that are not nominal. The controller will not attempt to maintain the subsystems at specific performance levels through these anomalies, but rather will select a response to the anomaly which will be determined by the controller to be most workable. The controller will consider current as well as scheduled tasks of each of the subsystems. It will also consider levels of criticallity of the separate subsystems based on life support of the crew and support of the mission and it will consider the status of subsystems being controlled as well as expected loads on each when making its determinations. The following paragraphs describe major functions of an integrating controller.

5.3.3.1 Electrical Power Load Management.

Figure 5.3-4 shows a block diagram for the electrical power load management part of an integrating controller's function. For this function, the integrating controller receives data that shows that the loads imposed on the electrical power subsystem are greater than the supply. These data could be dropping voltages or rapidly decreasing battery charge level.

The integrating controller will establish initial priority for those loads which are on line in the housekeeping area. Table 5.3-4 shows an example of such an initial priority list. Table 5.3-5 gives criteria that are used in determining the initial priority of loads. The integrating controller then adjusts the priorities for predicted load requirements and also adjusts according to the status of the subsystem using the power, e.g., the level of produced material that is in storage, the maintenance status or the failure probability status for that subystem. This adjusted priority list will be examined to determine which loads may be either shut down or reduced. The loads that can be shut down or reduced are so commanded and a time assessment is made by the controller to determine when the loads need to be resumed. The controller then manages switch on and switch out of loads through the period of power deficiency. It also makes the determination on whether degraded or emergency life support modes are necessary, and sets changes to limits on the individual life support subsystem and thermal control references as needed. In addition, the controller commands annunciation of conditions that relate to those changes in the life support modes. In summary, the subfunctions of power load management are:

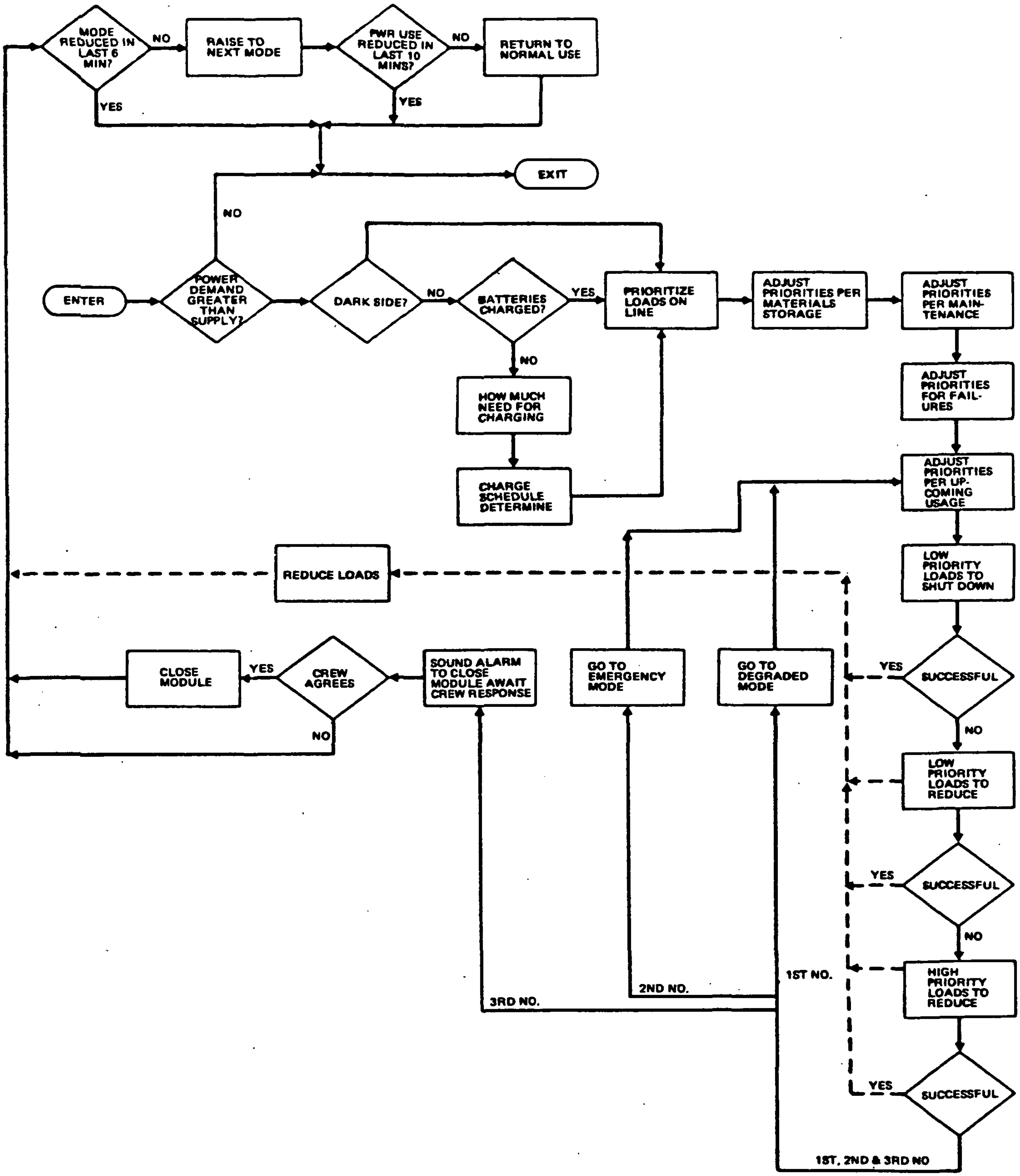


Figure 5.3-4. *Functional Block Diagram for Electrical Power Load Management by an Integrating Controller*

TABLE 5.3-4

Example of Load Priorities#

1. Power to water electrolysis generator for 0_2* - valves, pumps fans, electrolysis current.
2. Power to CO^2 removal units - valves, pumps, fans, steam heaters.
3. Power to dehumidifiers fans, pumps, valves, separators.
4. Power to cabin air heaters.
5. Power to Hygenic Water System* (this is placed fairly high on the list because, if production is low there would be a deficiency of hygiene water for 0^2 generation and CO^2 removal) - valves, pumps, VCD compressor, VCD heater and WQM.
6. Power to TCC unit (oxidizer, heater, fans, valves).
7. Power to CO^2 reduction unit (valves, pumps).
8. Power to wash water system* (valves, pumps, hyperfiltration heater, WQM, water heater).
9. Power to potable water system* (valves, pumps, WQM, water heater).

#Each item on list moves up in priority if high power need is coming up, but moves down if current need will be reduced in the near future.

*Each with full level of output substance moves down in priority list with respect to any which is depleted.

TABLE 5.3-5

Example of Criteria for Functional Criticallity

1.	Required to sustain the life of the crew.
2.	Short time allowed without replacement of life sustaining function.
3.	Required to maintain continuity of the mission.
4.	Short time allowed without replacement of continuity maintaining function.
5.	Required to sustain functions of more critical systems.
6.	Short time allowed before replacement of sustaining functions.
7.	Desired to maintain comfort status of crew.
8.	Short time allowed without replacement of comfort maintaining function.

1. Receive data on power deficiency.
2. Determine loads to be reduced or shut down.
3. Prepare system for shut down or reduction.
   a. Transfer of materials in storage.
   b. Closure of cabins.
4. Select degraded or emergency mode if needed.
5. Annunciate to crew.
6. Implement action.
7. Monitor time and change loads as needed to maintain system balance.

5.3.3.2 Materials Transfer Management

Figure 3.5-5 shows a block diagram for this function of an integrating controller. In order to perform this function, the integrating controller will receive data on the levels of water, oxygen, nitrogen, hydrogen, CO_2 and any other materials stored in various places around the space station. These data will be compared by the integrating controller with the schedule and location oriented needs for the materials. Any necessary transferral of such materials about the space station will then be determined and commanded. These determinations will be based on established schedule and location requirements for material as modified by up-to-date anomaly information. The onboard transferrals accomplished by this function will allow the space station to share onboard resources in the most effective manner to survive failures or disruptive events such as sustained concentrations of the crew or science experiments in a particular part of the space station. This material transfer process will be an integral part as necessary of any power shut down, redundant path selection, or maintenance rescheduling action by the integrating controller. Close off of modules or configuring for degraded or emergency modes will also be attended by materials transfer determinations and commands provided by the controller. In the event or over supply, the integrating controller will determine if dumping is an appropriate solution as well as where and when.

A summary of elements of this function include:

1. Data gathering on storage levels around the space station.
2. Determination of materials transfer needs against schedules or against locations.
3. Command actual transferrals.
4. Monitor time for follow-up transferrals back as necessary.
5. Decisions on the dumping of materials.

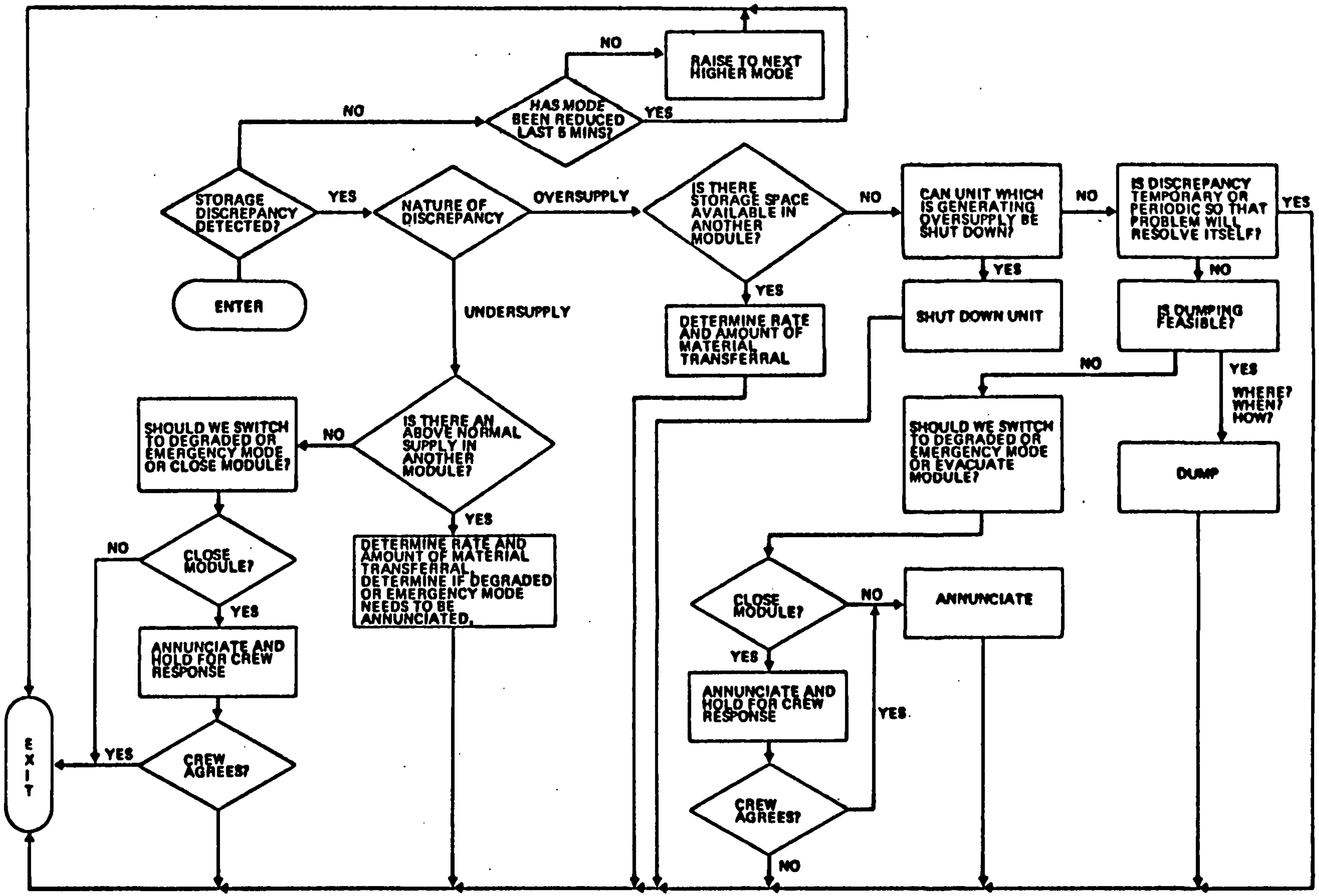


Figure 5.3-5. Functional Block Diagram for Materials Transfer Management by an Integrating Controller

a. Location of dumping.
b. Time of dumping.
c. Alternates to dumping.

5.3.3.3 Intersubsystem Failure Isolation

This function of an integrating controller will be performed after a fault goes undetected through the fault isolation processes within the subsystems. This diagnostic function will consider failure indications across subsystem boundaries and will be largely interactive with the onboard crew to help them trace down those failures. The function will have numerous paths that will be followed in response to inputs from the astronauts to identify the fault and recommend the corrective action. Figure 5.3-6 illustrates how such a function could be structured. A summary of elements of this function include:

1. Data gathering on existence of inter-subsystem fault.
2. Annunciation to crew.
3. Interactive process with crew to isolate fault.
4. Annunciate recommended action to crew.

5.3.3.4 Intersubsystem Redundant Path Selection

Figure 5.3-7 shows a functional block diagram for the redundant path management part of the integrating controller process. For this, the controller receives data indicating a failed element in one of the automated housekeeping systems. The controller will survey the configurations existing to determine if a redundant path is available. This will be done considering any previous failures not repaired or redundant path selections for maintenance shut downs which may be in effect. Then available paths will be selected, but preparations will first be commanded by the integrating controller as needed. These include transfer of materials such as water from a system to be shut down to one that will experience extra use during the failure, power adjustments, and modifications to the maintenance schedule. Then the switch of function will be made to the redundant path. In the event that a redundant path is not available or will only be available for a limited time (due to materials shortages or essential maintenance schedules), the integrating controller will decide if a degraded or emergency mode with or without cabin shut down is needed. It will then annunciate the mode or shut down to the crew and will command and materials transfer and power adjustments needed to prepare for the selected mode. The limits on the individual life support subsystem or thermal references will be adjusted to levels consistent with the selected mode shift. These functions of the integrating controller are summarized by the following:

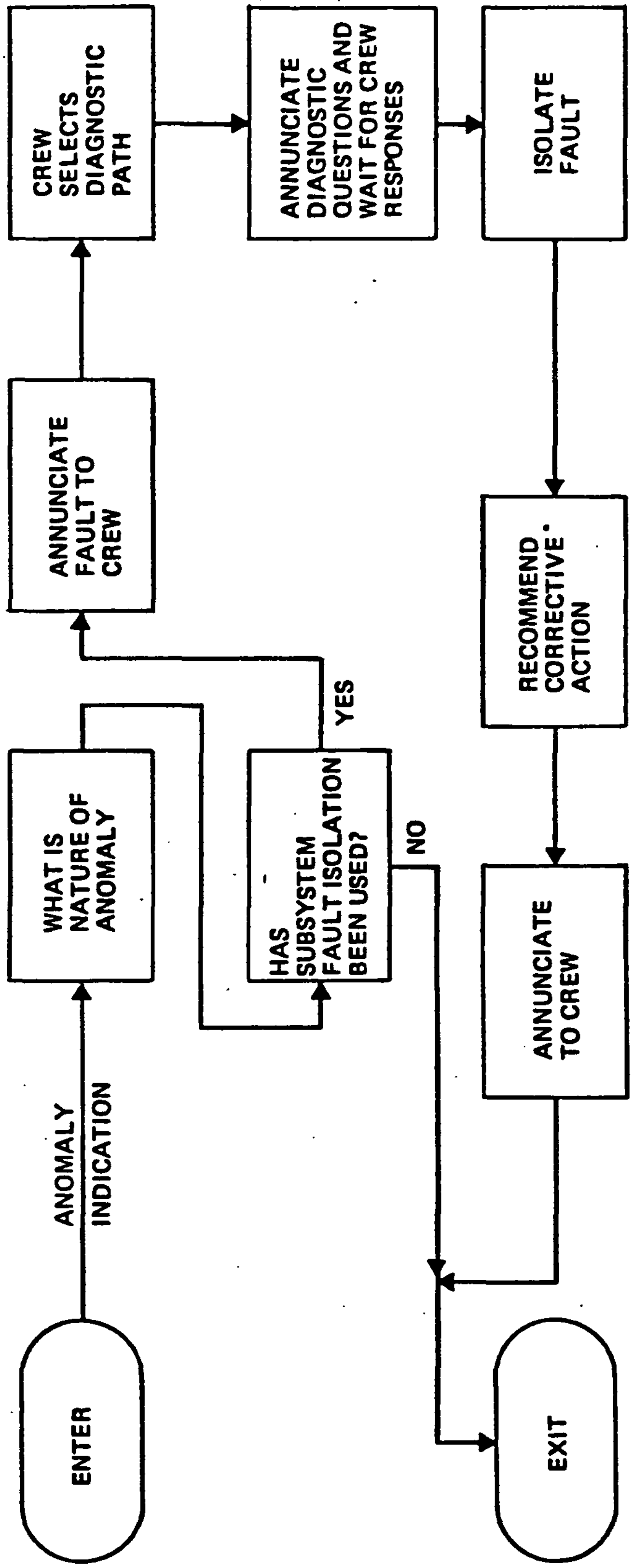


Figure 5.3-6. Functional Block Diagram for Inter-Subsystem Failure Isolation Using Integrating Controller

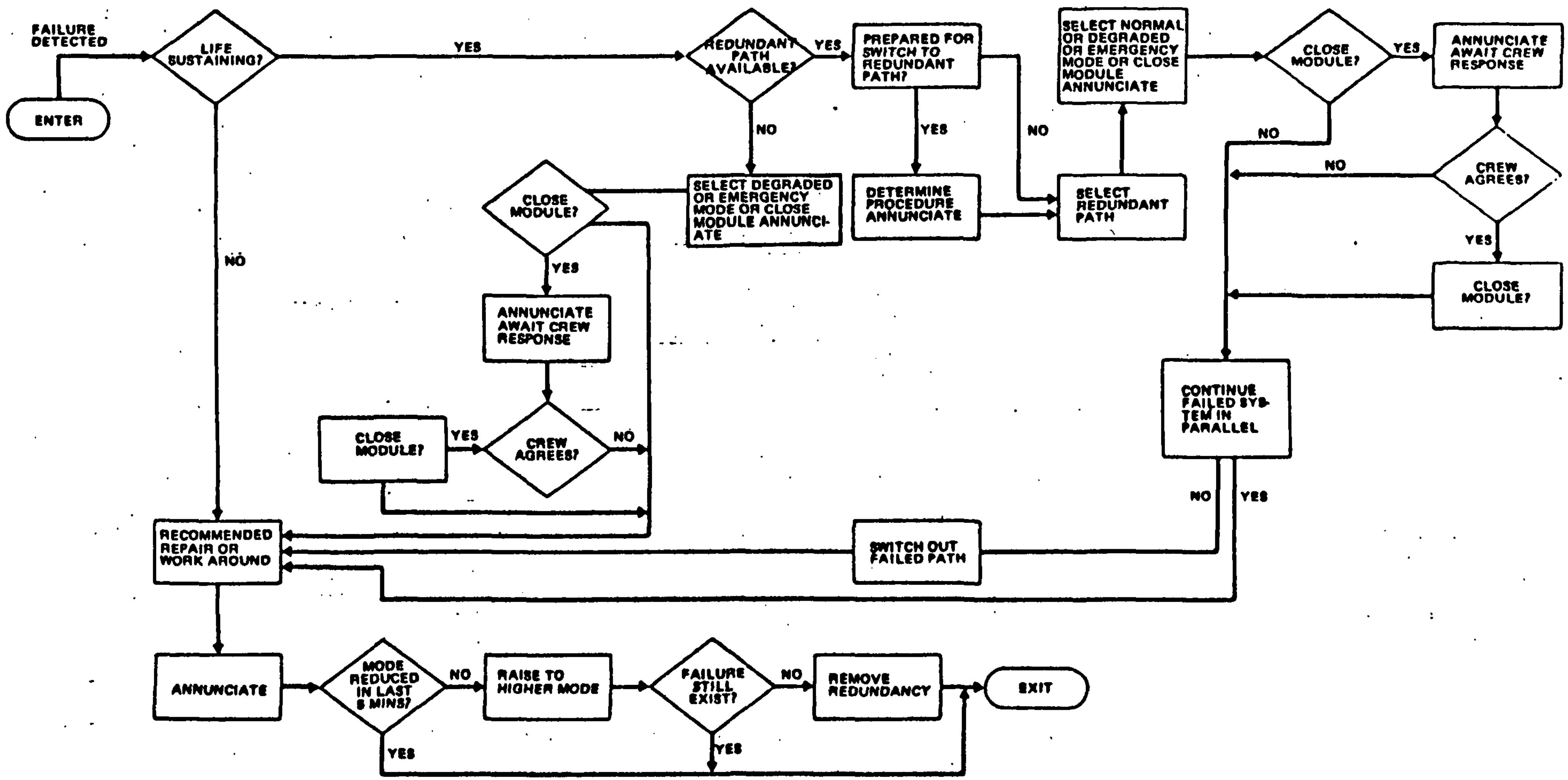


Figure 5.3-7 Functional Block Diagram for Inter-subsystem Redundant Path Selection by an Integrating Controller

1. Receive data on failed system path.
2. Determine if redundant paths are available.
3. Prepare system for switch to the redundant paths.
   a. Transferral of materials.
   b. Adjustment of maintenance schedules.
   c. Power usage adjustments.
4. Select degraded or emergency mode if needed - perform necessary adjustments.
5. Annunciate to crew.
6. Implement action.

5.3.3.5 Maintenance Schedule Management

This function of the integrating controller is displayed by the block diagram of figure 5.3-8. The normal maintenance schedule for all housekeeping subsystems will be established prior to space station deployment. (Usually as the station is being developed.) The integrating controller will annunciate maintenance actions periodically to the crew in accordance with that schedule. The controller will also command appropriate adjustments to the subsystems; i.e., power shut downs, materials transfers, or redundant path selections on schedule to prepare for the normal maintenance actions. Based on data collected on failure modes, operational conflicts, maintenance supply logistics problems, or astronaut time conflicts, the normal schedule may be modified by the integrating controller using coordinated adjustments. Thereafter, the controller will manage maintenance accordingly and will determine any modifications needed in the logistics requirements for maintenance materials or manuals. These functions are summarized by the following:

1. Receive data on schedule problem.
2. Determine if schedule problems are:
   a. caused by system failures.
   b. incompatibility with operations.
   c. failure to serve maintenance needs.
3. Determine schedule change and impacts.
4. Determine logistics changes needed.
5. Annunciate to crew.

This function will be largely interactive with the onboard crew and the integrating controller will be receiving inputs and providing outputs through an interactive terminal.

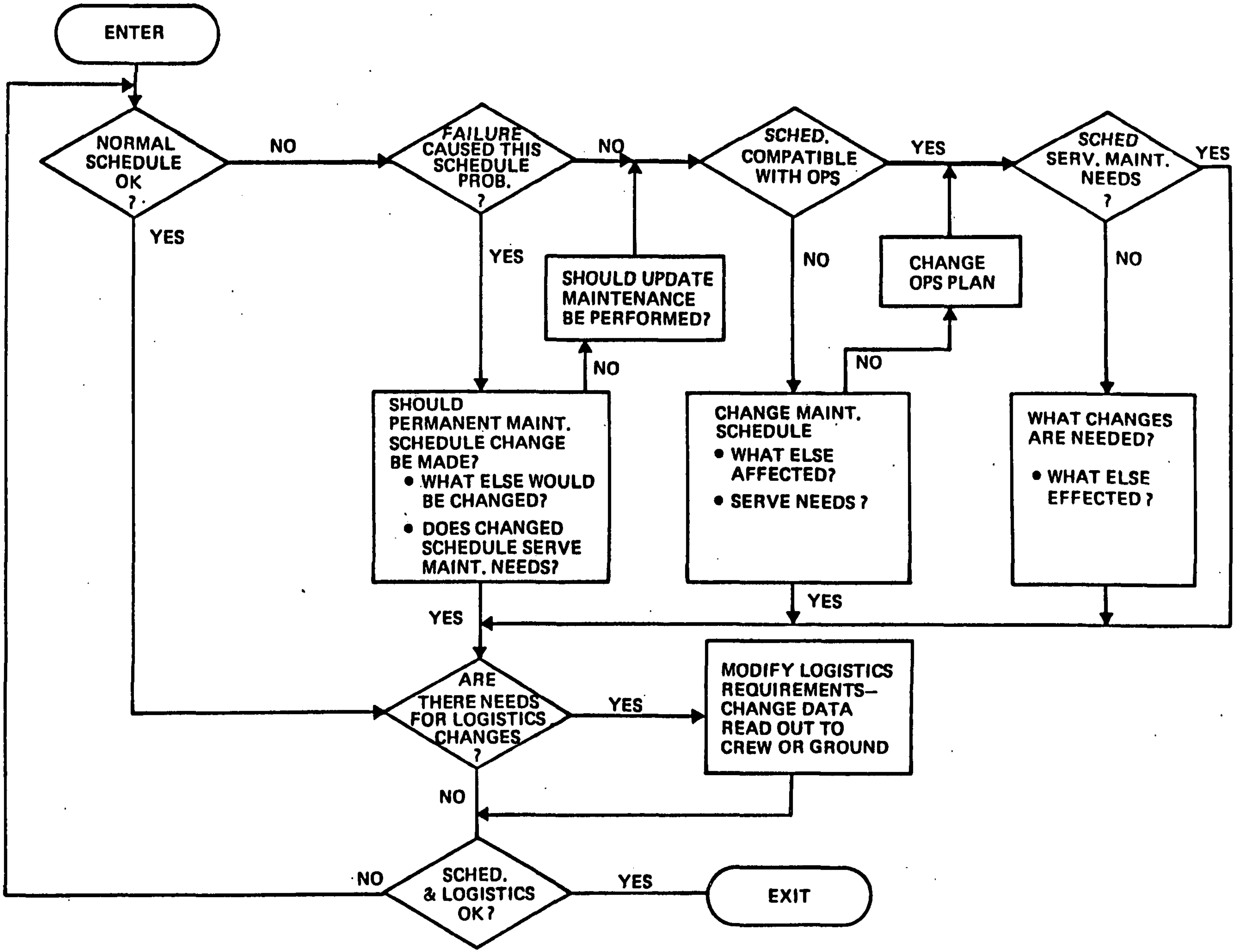


Figure 5.3-8. Functional Block Diagram for Maintenance Schedule Management by an Integrating Controller

5.3.3.6 Start-up Integration

The integrating controller will support the start-up process by setting parameter levels for each step of the initialization. These would then be adjusted to account for such conditions as failure in existence or being handled by workarounds, power load variations, crew size and dispersement variations, materials levels and deployments and others which could modify the start up. The controller will then check the parameters against the set levels and advise the crew when the next step can be taken. Figure 5.3-9 gives a block diagram illustration of the function and the following summarizes the steps.

1. Receive input that initiates start-up integration.
2. Determine set of nominal parametric values sequenced to the start-up process.
3. Adjust values to reflect current conditions in the system.
4. Trace parameters against adjusted values.
5. Annunciate instructions on start-up steps to crew.

5.3.4 Functional Scenarios

The following scenarios were developed to describe the operating environment for the integrating controller. The first scenario is for initialization of a space station system. This scenario is conceptual in nature and as such is subject to modification as the space station design develops. The second scenario is for a shift in life support modes on a space station.

5.3.4.1 System Initialization Scenario

This scenario is to describe events that might occur as a space station module is initialized for habitation by the crew. It is assumed that the shuttle is attached and that the crew relies on the shuttle systems to support the initial EVA. As can be seen, no attempt is made to work out the specific number of orbits for this process. The initialization crew will start out using EVA and then will go to shirt sleeves after orbit L. The initialization crew would be two or possibly three astronauts and would be joined by the remainder of the crew after orbit W.

	Orbit
1. Close cabins and establish initial atmosphere	N
2. Cabin power available	N + M
3. Cabin heat exchangers	N+M+1 = L
4. Cabin Trace Contamination Control (TCC) on	N+M+1 = L
5. Cabin dehumidifiers on	N+M+1 = L

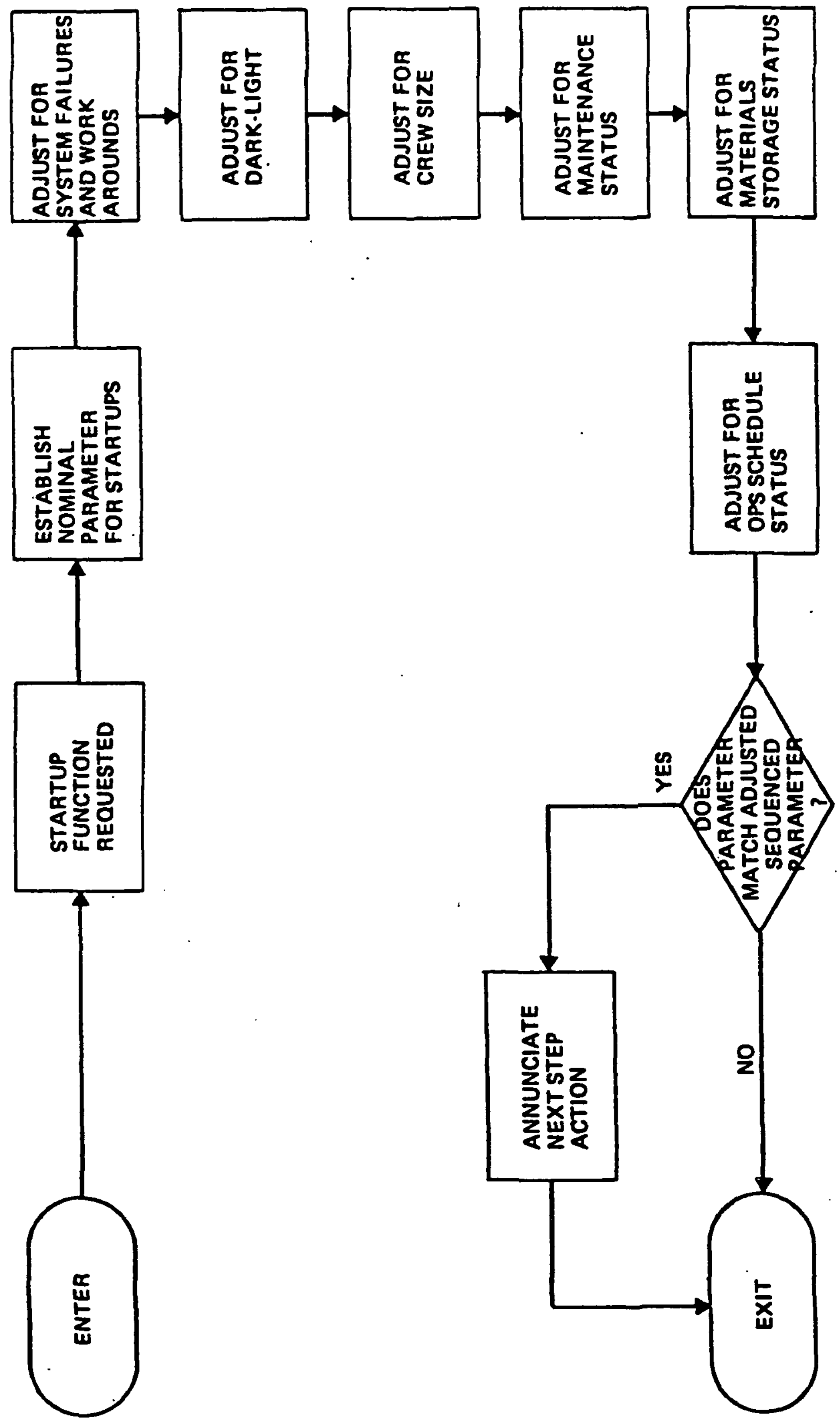


Figure 5.3-9. Functional Block Diagram for Startup Integration by an Integrating Controller

6. O_2 generators on	L+R = Z
7. N_2 supply opened	L+R = Z
8. Cabin air heaters on	L+R = Z
9. CO_2 removal on	Z+1
10. CO_2 reduction on	Z+2
11. Crew begins cabin occupancy	Z+S = W
12. Potable water loop on	Z+S = W
13. Hygenic water loop on	Z+S = W
14. Wash water loop on	Z+S = W

Between 1. and 2., several crew members using EVA will inspect and set up cabin interior in a physical sense. This will take M orbits to accomplish and then the power to the cabin will be initialized. After an additional orbit for EVA inspection, the cabin heat exchangers, TCC, and dehumidifiers will be turned on. This will include astronauts installing LIOH sorbant units and charcoal units in the TCC and inspecting the progress of the system turn on visually. Sensors in the TCC, as well as temperature and humidity sensors will be monitored by their respective control systems and the integrating controller will be notified when readings meet specifications. The integrating controller will then communicate to the initialization crew that the O_2 generators and N_2 may be turned on. The time required for the TCC, dehumidifiers and heat exchangers to meet spec will be compared with the expected time by the controller, and if a discrepancy exists it will advise the EVA crew on possible repairs or adjustments. Once O_2 and N_2 are flowing to the cabin the air heaters will be turned on and their operation inspected by the initialization crew. The integrating controller will be notified when the systems meet spec, and it will compare performance with the expected time and notify crew on adjustments to the system. The CO_2 removal and reduction systems will be turned on as soon as the O_2, N_2 and air heater systems are determined to be performing properly. Again, the controller determines if the systems reach specified performance in the prescribed time and notifies the crew that is conducting the initialization of any adjustments which are needed. Once the CO_2 removal and reduction systems are on line the entire crew, may inhabit the cabin. The water loops will then be closed with the integrating controller monitoring elapsed time against the expected period and providing annunciation to the crew if any repairs or adjustments are needed.

During this entire process, the controller will perform its power, materials transfer, and redundant path management functions for those systems that are on line.

5.3.4.2 Mode Shift Scenario

This sequence is the result of a change in the life support subsystem operating mode between the nominal, degraded, or emergency set points. Again this is a conceptual sequence of events to be described more specifically after the space station design becomes more defined.

1. Mode change selected either by crew or the integrating controller.
2. The integrating controller then adjusts control limits for each automatic system reference to correspond with selected mode.
3. System configured for mode shift as necessary by commands from the integrating controller.
    a. Materials transfer.
    b. Power adjustments.
    c. Path selection.
4. Maintenance schedule adjusted as needed.
5. Annunciation to crew.
6. Implement mode shift.

Astronaut adjusts the life support set point from nominal to degraded or emergency mode or the mode shift is selected by the integrating controller in response to deficient operation due to failure, power deficiency, materials enbalance, or maintenance action.

Integrating controller then adjusts control system references to each subsystem automation unit in a scheduled and locational pattern based on the location and status of the deficiency and the status of the subsystem at the time when the deficiency is detected.

The integrating controller also checks levels of materials in storage, monitors power deficiencies and failure modes, and commands appropriate transfers, load reductions, or redundant path actions. The integrating controller reschedules routine maintenance to occur after the selected degraded or emergency mode is over whenever possible.

If the action involves the shut down of a space station module, the integrating controller will command the flow of materials from the module to be shut down to ones to be occupied and will verify the egress of all crew members from that module before allowing the hatch to be closed.

5.3.5 Hardware and Software Elements

An integrating controller will consist of on-board central and distributed processors that will initially be supported by an earth-based central data processing facility which can be used by employing the telemetry link. The processing functions will be largely in the on-board central processor for all decision making and command generating. The distributed processors will be used for data collection and command execution functions. The earth bound facility will be used for some off-line comparisons and determinations especially for failure diagnostics and logistics control. Figure 5.3-10 shows a typical processor hierarchy and data path connection concept for a integrating controller. The diagram indicates where the functions are in the central processor and where they are distributed.

The following paragraphs summarize the separate processor functions.

5.3.5.1 Data Collection Processors

These would be distributed processors located near the subsystem elements where the data is being collected and would perform the following processing functions:

1. Select data to be sampled.
2. Select rate of data to be sampled.
3. Select sequence of samples.
4. Process sample data for presentation to the central processor.

5.3.5.2 Comparison Processor

This would be an entry processing element of a central processor and would perform the following functions:

1. Compare data received with past data.
2. Compare data received with standard values.
3. Compare data received with other data received.

These comparisons will be used by the decision making processor.

5.3.5.3 Data Storage Processing

This would be an entry processing function of a central processor. The data coming into a central processor will be stored or discarded and the management of that process as well as a review of the data in storage for purposes of determining what is to be purged will be the function of the data storage processor.

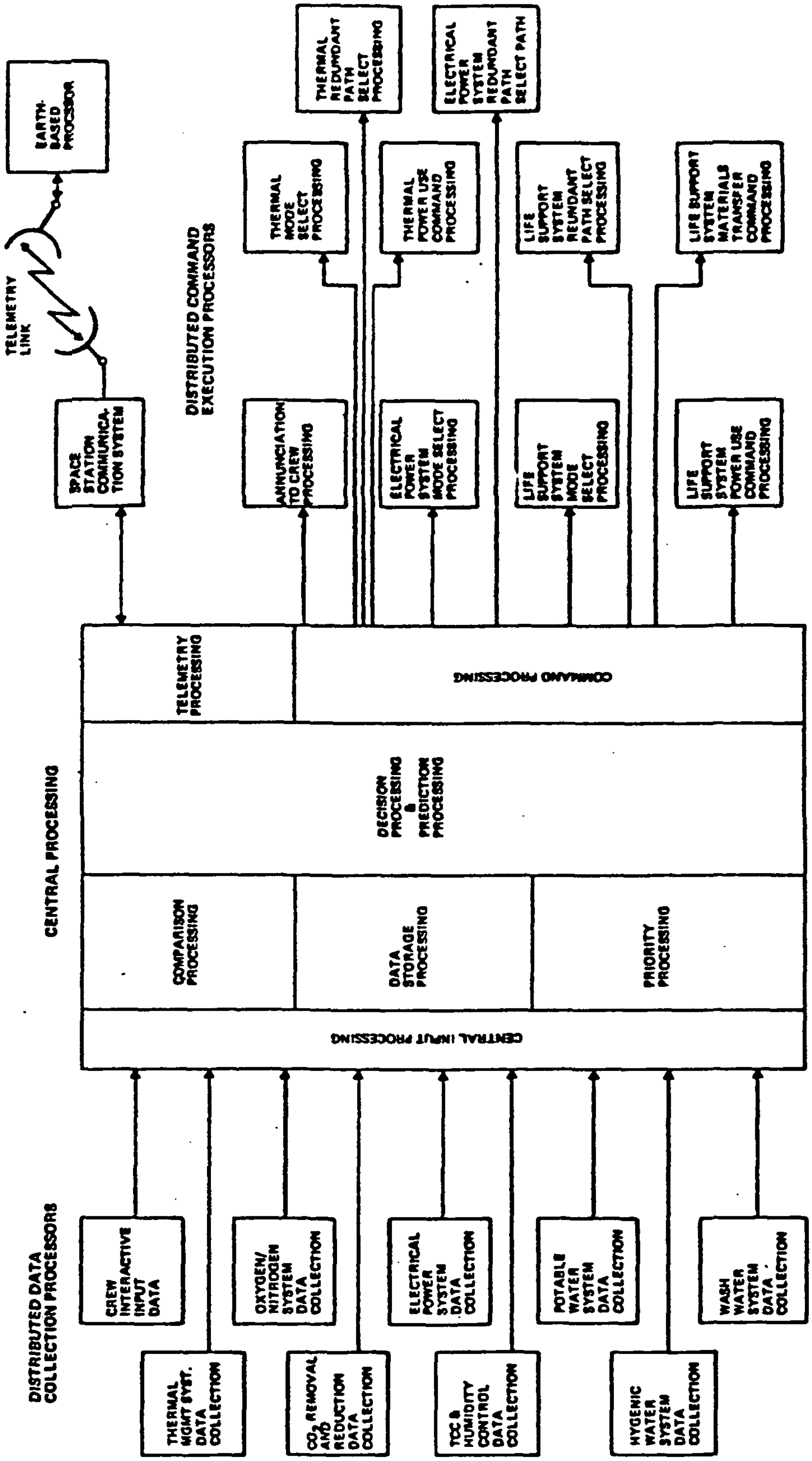


Figure 5.3-10. Processing Functional Diagram of Integrating Controller for Automated Housekeeping

5.3.5.4 Decision Processor

This is a principle function of an onboard central processor and includes the following processing subfunctions:

1. If total power supplied data is less than the total demand data, process a power reduction decision.

2. If failure data is received process a redundant path selection decision.

3. If materials storage level data is out of agreement with predicted levels, process a materials transfer decision.

4. If data indicates a change in maintenance schedule as a result of action taken on failure events, a schedule revision is selected.

5. If data indicates that performance is not being met, a decision on going to degraded or emergency mode will be processed.

6. If localized performance degradation exists as shown by data received a decision is processed on closing off a space station module.

7. If a problem indication is detected process a failure isolation interactive routine and the resulting failure identification decision.

8. If a start-up mode is requested process a start up support and interactive routine and process start up step decisions.

5.3.5.5 Predictor Processing

The decision processor is supported by several other processor functions. One of these is the predictor processor. It performs the following actions:

1. Predictions will be made as to the consequences of actions being considered by the decision processor.

2. Predictions will be processed to identify when an action that has been commanded must be changed or new decisions must be made.

5.3.5.6 Priority Processing

Another function that supports the decision maker is the priority processor. As part of the decision making process, prioritized lists will be established and revised by the priority processor.

5.3.5.7 Command Processing

The actions, sequencing, and quantitative aspects of commands will be processed once decisions are made. This function will be accomplished in part by the central processor and in part by distributed processors located where the commands are executed.

The central processor will issue the command in general terms to the distributed processors. Each distributed processor will interprete the general command for the particular system element that the distributed processor is supporting.

5.3.5.8 Earth Based Processing

Failure diagnosis, logistics modifications, problem solutions for communication to the crew would be processed initially by an earth-based data processing facility when time delays from off-line processing could be tolerated. This facility could also be used for simulation and check out of software modifications prior to implementing them in the onboard system.

5.3.6 Expert Systems Considerations

This section consists largely of the responses received to the questions poised under section 5.2.4. The following functions of the integrating controller were indicated by those responses to be definite candidates for some expert systems processing.

1. Electrical power load management—the MSFC has a study that is being conducted by Martin Marietta and the indications from that study are that expert systems apply to this function.

2. Redundant path selection—work is being done to apply expert systems to this problem for nuclear power plants.

3. Maintenance schedule management—this general area is considered to be a promising application of expert systems.

All of the other functions were considered by the responses to be good possibilities for at least partial application of expert systems.

In theory, expert systems can't do anything that conventional automation can't and vice versa. In practice, there are differences in application that favor one approach over the other. Conventional automation seems to be best if the problem is highly deterministic or when there is a good theory. Expert systems seem to be best in situations where repetitive, comparatively low-level judgements are made. Judgements, in this case are decisions for which there are no clear cut guidelines.

The mode select scenario seems to have a substantial judgemental aspect to it. This is illustrated by the following example:

Assume we have gotten into a situation as shown in the figure 5.3-11. Because there is no H_2, we cannot reduce the CO_2. This means we cannot empty the CO_2, storage container, which in turn means we cannot purge the SAWD canisters in the CO_2 removal unit. This means that the CO_2 level in the cabin may increase to an undesirable level.

There are several responses that may be made to this situation. Some include the following:

1. Dump some CO_2 overboard—this is undesirable because it represents the loss of resources, may contaminate sensors, and violates "no dump" space station ground rule.

2. Generate some O_2—this will create H_2 so that we can reduce the CO_2. However, this will take time to do, and in the interim, the CO_2 may become degraded.

3. Transfer crew to another cabin—this will solve the problem unless the CO_2 removal unit in the other cabin is operating in a degraded mode, in which case we make things worse in the other cabin.

4. Transfer CO_2 to another cabin—this will also solve the problem unless the other cabin has a problem too.

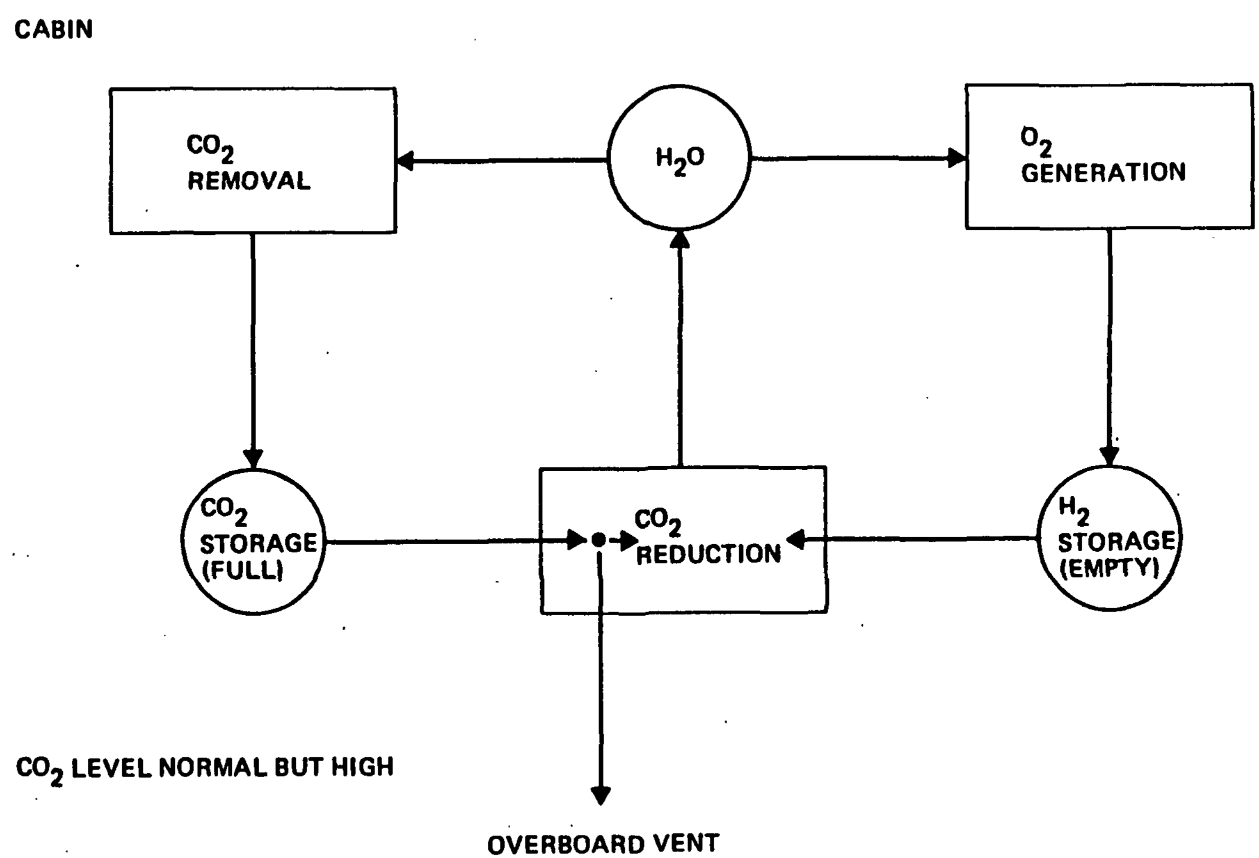


Figure 5.3-11. Air Regeneration Unit Diagram

None of these responses is completely satisfactory. In addition, there may be some secondary factors. For example, a shuttle resupply flight might be delayed, which means that it is extremely desirable to conserve resources.

It is not obvious that there is a technical answer of what to do in a situation like this. The approach is to ask what would a space station commander do given this situation? Design the mode selector to do the same thing. This is the expert systems approach.

On the other hand, not all aspects of the integration control problem require expert systems technology. A hybrid controller may be best. With such a controller, there will be several expert system components working with conventional parts of an integrating controller. This is because expert systems are best if applied so that each handles a single specific type of problem. The integrating controller involves solving several problems that are quite distinct from the standpoint of an expert system. Techniques can be applied to use expert systems that integrate several other expert systems and the conventional elements using a blackboard concept. Figure 5.3-12 shows how such a concept might be structured.

Using today's technology, expert systems are not good choices for problems that require fast solutions (less than minutes). Assuming that life support system operation is synchronized with the sunny part of the orbit, an expert system decision model would run once or twice per orbit (mainly to set the system up for the transition from shadow to sun). It would run more often if out-of-the-ordinary situations occurred and that may require advancement in current technology.

Clearly, the onboard integrating controller needs expert systems, but even if it did not, there might be advantages to using expert systems technology. For example, the explanation capability often exhibited by expert systems would be helpful during space stations subsystem development. If an integrating controller were built using conventional automation, it would be so complex and difficult to understand that it would be desirable to train the crew with an expert system that would explain the behavior of the integrating controller.

Any estimate of the size of the expert systems parts of an integrating controller is constrained by the following:

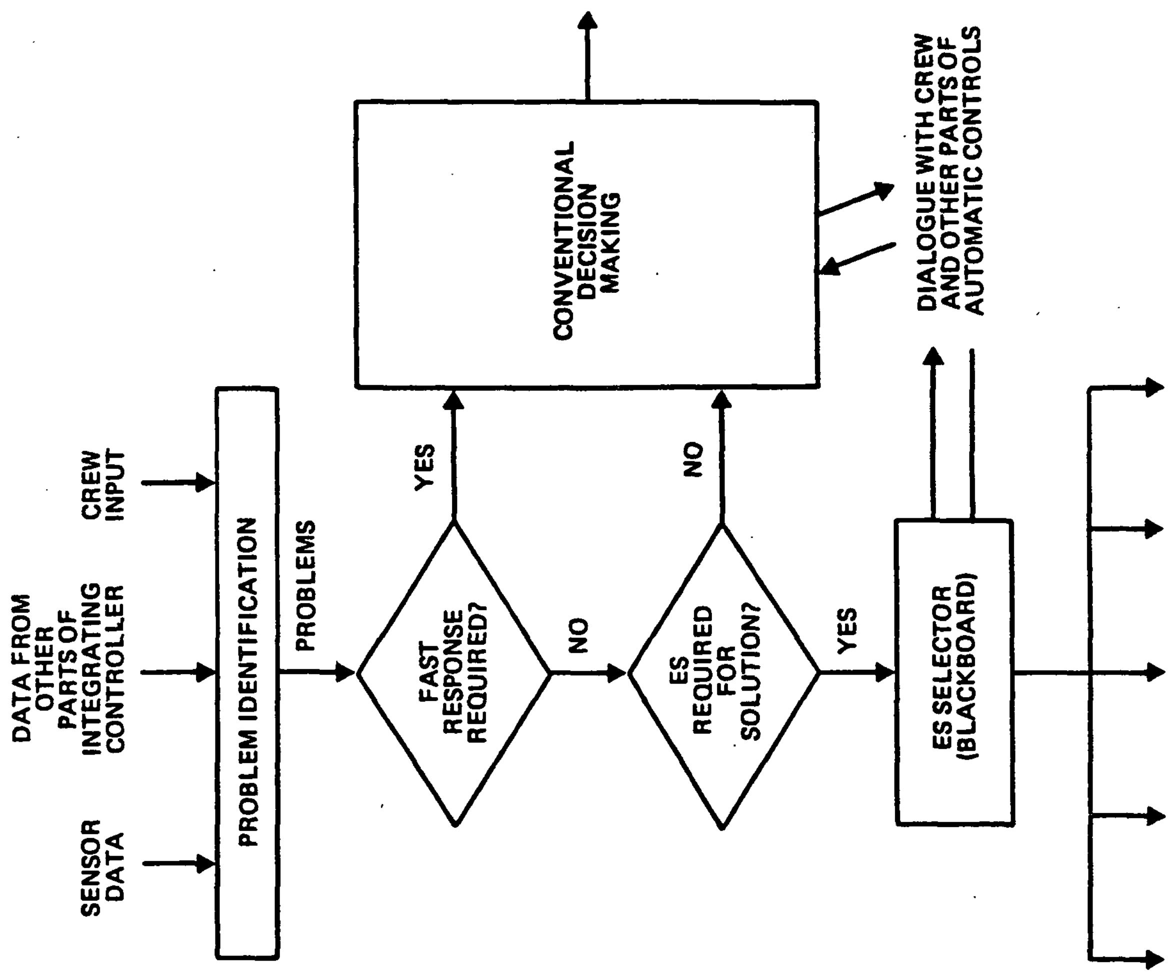


Figure 5.3-12. Input Processor Concept

1. The preferred current method of developing an expert system is to use an expert system language analogous to a programming language for conventional automation. The number of statements in a conventional program can vary drastically depending on the language. In the case of expert systems, there is probably at least a 3:1 variation in number of rules depending upon the language used.

2. Expert systems do not have to be developed using rules. Rules are a knowledge representation technique. There are other ways of representing knowledge including:
   a. Logic
   b. Networks
   c. Frames
   d. Hybrid

This is one reason why an integrating controller would involve several expert systems for its different types of functions.

Given the above caveats, it was estimated that as an example, the inter-subsystem failure isolation function expert system would involve from 1,000-3,000 rules, and in that case using rules for estimating is probably a good way to go.

Factors to consider when describing whether to use space-borne or ground-based computers for the integrating controller include:

1. Criticality—will the astronauts be threatened if access to the integrating controller is interrupted?

2. Resource usage—does the integrating controller use an excessive amount of space borne computer resources?

3. Data bandwidth—does the integrating contoller process so much data that transmitting it to earth would jug up the communications channels?

Because of the criticality of the failure isolation function and redundant path selection function, they would be high priorities for space borne implementation. Maintenance scheduling could probably be ground based at least in the early stages of the space station.

In order to estimate the space borne computational capability required, several assumptions will be made:

1. The expert systems used will be programmed for the onboard system using the LISP programming language. (LISP is a heavy user of resources).

2. The space station has a distributed processing system consisting of general purpose as well as special purpose processors.

3. General purpose processors are machines with 32 bit CPUs, 2 MIPS throughput and 1 megabyte of memory.

4. Mass storage will be available to store expert systems rules when not actively being processed.

Based on these assumptions, it is estimated that an expert system implementation would require a general purpose processor for active processing of each expert system function of the type exemplified by inter-subsystem failure isolation system.

Any large expert system might require a special purpose processor, and unless the function was extremely critical for crew safety, it would not be space borne.

To estimate the effort needed to develop an expert system a single function such as the failure isolation is guessed to require at least 5-10 man-years of effort. Assuming one expert system per function, 30-60 man-years of effort would be required. (Currently 5 man-years seems to be the quickest any expert system can be developed).

All of this indicates that expert systems have a role to play in the integrating controller concept, but that they are, when based on current technology, heavy users of computational resources and also of development effort.

5.3.7 Trade Study Comparisons

The results of the concept characterization studies for an integrating controller are basically the definitions of functions to be performed by such a controller and concepts for processing of those functions on board the space station or on the ground using distributed as well as centralized architecture. This paragraph discusses the comparisons conducted with respect to these characterizations.

Figure 5.3-13 gives a trade of the functions of the integrating controller against five fairly nonquantifiable criteria. These are:

1. Frequency of use–this means the relative number of usage instances for the function over the operation period of a space station (one time, often, continuous).

2. Autonomous processing–this is an assessment of how much the astronauts will want the function to be autonomous.

3. Essential for safety–functions are assessed with respect to how essential they are to maintaining a space station that is safe for the astronauts, the visiting shuttle and the space station missions.

4. Deterministic processing–this is an assessment of how much of the function is based on data and how much is based on know-how of people.

5. Durability–this is an assessment of wheather the use for the function will increase or decrease as the space station matures.

The cumulative rankings of the six functions against the criteria used gives the following results:

Electrical power load management	=	7
Materials transfer management	=	9
Intersubsystem failure isolation	=	10
Intersubsystem redundant path select	=	11
Start-up integration	=	17
Maintenance schedule management	=	20

TECHNOLOGY DISCIPLINE:	INTEGRATION OF AUTOMATED HOUSEKEEPING					
TECHNOLOGY ADVANCEMENT GOAL:	TO REDUCE COST OF MAINTAINING THE HOUSEKEEPING FUNCTIONS ON A SPACE STATION WHILE ENHANCING CREW SAFETY AND COMFORT.					
SPECIFIC TRADE:	COMPARE SIX FUNCTIONS OF AN INTEGRATING CONTROLLER AGAINST CRITERIA OF: USE FREQUENCY, INTERACTIVE SUPPORT, ESSENTIAL FOR SAFETY, DETERMINISTIC PROCESSING AND DURABILITY.					
TRADE OPTIONS ➡ NUMBER DESCRIPTION	OPTION 1 ELECT. POWER LOAD MGT	OPTION 2 MATERIALS TRANSFER MGT	OPTION 3 INTERSUBSYS FAILURE ISOLATION	OPTION 4 INTERSUBSYS REDUNDANT PATH SEL.	OPTION 5 MAINTENANCE SCHEDULE MGT	OPTION 6 STARTUP INTEGRATION
FREQUENCY OF USE	OFTEN TO CONTINUOUS BECAUSE SPACE STATION GROWS AND EXPERIMENTS CHANGE SO POWER UNBALANCES WILL POP UP FREQUENTLY. FAILURES ALSO CAUSE UNBALANCED POWER USE TO SUPPLY.	OFTEN TO CONTINUOUS BECAUSE OF SPACE STATION GROWTH AND EXPERIMENTAL CHANGES ALSO THIS FUNCTION IS AFFECTED BY LOCATIONAL CHANGES AROUND THE SPACE STATION OF CREW OR EXPERIMENTS.	BECAUSE THE OCCURRENCES OF FAILURES ARE SOMEWHAT UNPREDICTABLE, THIS FUNCTION NEEDS TO BE CONTINUOUSLY AVAILABLE BUT PERHAPS NOT ON LINE UNTIL THE SUBSYSTEM FAILURE IS INDICATED–OCCASIONAL USE–CONTINUOUSLY AVAILABLE	WOULD BE USED IN EARLY STATION AFTER OPTION 3 FUNCTION HAD BEEN USED. LATER THIS MIGHT BECOME AUTONOMOUS AND THEN IT WOULD BE ON LINE. CONTINUOUSLY AS WOULD OPTION 3.	OCCASIONAL TO OFTEN BECAUSE THE ADJUSTMENT OF MAINTENANCE SCHEDULE COULD BE PUT OFF UNTIL A QUIET PERIOD EXISTED FOR THE COMPUTER.	THIS FUNCTION WOULD BE CALLED UP MUCH AS THE OPTION 3 AND OPTION 4 FUNCTIONS WOULD BE CALLED UP. THIS FUNCTION, HOWEVER, WOULD NOT BE A LIKELY CANDIDATE FOR AUTOMATION– OCCASIONAL.
RANKING	1	1	2	2	4	3
AUTONOMOUS PROCESSING	ASTRONAUTS WOULD PROBABLY LIKE THIS TO BE AUTONOMOUS	THIS WOULD ALSO BE A GOOD CANDIDATE FOR AUTONOMOUS IMPLEMENTATION	EARLY ON THIS WOULD BE INTERACTIVE. ASTRONAUTS WOULD PROBABLY LIKE TO BE ADVISED AFTER THE FACT	AGAIN ASTRONAUTS WOULD PROBABLY PREFER THAT THIS EVENTUALLY BE AUTOMATIC WITH AN ADVISORY OUTPUT.	ASTRONAUTS WILL WANT THIS TO BE INTERACTIVE.	THIS WILL BE INTERACTIVE AND ASTRONAUTS PROBABLY WILL AGREE.
RANKING	1	1	2	2	4	3
ESSENTIAL FOR SAFETY	THIS FUNCTION HAS A SECONDARY RELATIONSHIP TO SAFETY	SOMEWHAT RELATED TO SAFETY	THIS FUNCTION IS ABSOLUTELY NEEDED FOR A COMPLEXED AUTOMATED SET OF SUBSYSTEMS	THIS FUNCTION IS ALMOST AS ESSENTIAL AS OPTION 3.	NOT PARTICULARLY RELATED TO SAFETY.	SOMEWHAT RELATED TO SAFETY.
RANKING	2	2	1	1	5	4
DETERMINISTIC PROCESSING	HAS A RELIANCE ON KNOW-HOW AT LEAST FOR EARLY SPACE STATION	SOMEWHAT MORE DETERMINISTIC THAN OPT 1	LARGELY KNOW-HOW BASED AT FIRST–MAY BECOME DETERMINISTIC WITH EXPERIENCE SAME AS OPTION 1	ABOUT THE SAME AS OPTION 3	THIS ONE WILL BE JUDGMENTAL BUT WILL ALLOW FOR MORE DATA COLLECTION BECAUSE TIME FOR DECISIONS IS GREAT	THIS ONE SHOULD BECOME DETERMINISTIC RATHER RAPIDLY BUT USE WILL DROP OFF TOO.
RANKING	2	3	2	2	4	4
DURABILITY	PROBABLY WILL TAKE A LONG TIME BEFORE THIS FUNCTION WILL GO AWAY–BECAUSE OF THE CHANGING STATION	LIKE 1 EXCEPT THAT TIME FOR DECISIONS IS GREATER SO MORE DATA CAN BE GATHERED	WILL GO AWAY SOONER THAN 1 BECAUSE EFFORT WILL ALWAYS BE GREAT TO ELIMINATE CRITICAL FAILURE MODES.	SOMEWHAT LESS DURABLE THAN 3	PROBABLY WILL BE AROUND AS LONG AS SPACE STATION IS EVOLVING	THIS ONE SHOULD GO AWAY FAIRLY RAPIDLY ONCE THE SPACE STATION SETTLES DOWN A LITTLE.
RANKING	1	2	3	4	3	3
	7	8	10	11		

Figure 5.3-13 Trade of Integrating Controller Functions

This indicates that the start-up integration and maintenance schedule management are of lower priority than the other four functions. This seems somewhat reasonable since the space station would need the first four for smooth and safe operation while the last two would be more like convenience functions.

The trades between distributed versus centralized architecture are based on mass, vulnerability, maintainability, and cost.

1. Mass–greater on-orbit mass with distributed, but modern computer technology may make the difference trivial.

2. Vulnerability–greater vulnerability to failures with centralized because functions are not repeated. This means that one location failures could result such as thermal contact failure, grounding failures, meteroid hits, etc. Even with voting the centralized system would be more vulnerable to failures.

3. Maintainability–distributed system is more easily maintained because repeated processing allows natural on-line/off-line configurations. Also standardized components are more easily replaced.

4. Cost–this trade is not clear. There is more hardware with a distributed system but it is standardized and therefore not as expensive. There is more network operating system software with a distributed system but interfaces are defined by the standardized hardware.

In general a distributed architecture is favored where the requirements for computing capacity indicated by the function do not dictate extremely large units that would not be practical to duplicate on board the space station.

The trades between onboard versus ground processing are based on the cost of ground facilities to communicate with the space station as opposed to the cost of placing the facilities on the station with the mass and logisitics penalties as well as the the qualification costs. Also, onboard mission control would be less labor intensive and therefore those costs would tend to be less although the labor rates would be higher in space.

The comparison of a fully automatic system versus one where the astronauts interact thru a computer terminal involves human preferences. In many cases the astronauts would probably prefer not to be bothered with routine diagnosis and corrective action but in others such as scheduling and logistics the astronauts would probably want to maintain control. In a few cases such as attitude control or some power control the diagnosis and corrective action could require faster response than that which is consistent with human capability and that would favor the fully automatic approach. Finally the acquisition of a knowledge base to develope the integrating controller system will benefit by the interactive experience of astronauts during the early missions. All of this indicates that the early space station will be characterized by a great emphasis on interactive controllers but as the station matures many functions will want to become fully automatic.

5.3.8 Cost and Benefits Analysis

Based on the integrating controller characterization developed in this study and the trade study considerations identified above an update of the cost and benefits for advancing the expert systems technology can be established. In section 4.1.8 of volume II of the Advanced Platform Systems Technology Study Final Report a cost and benefits estimate was made for the expert systems technology for an integrating controller. In the current study we have developed a more detailed description of the functions of the controller and have focused on the programatic trades with respect to those functions and that allows a more realistic estimate of costs and benefits.

The following assumptions are established for the cost update of this current study.

1. Six expert system functional elements plus one expert system selection element will be considered.

2. Each element is equivilent to one R1 expert system program (850 rules) except the intersubsystem failure isolation element, which is assumed to be 2,000 rules per section 5.3.6. This gives a total of 7,100 rules for the integrating controller expert systems.

3. Based on the productivity of section 5.3.6 each rule requires 2 days of labor to develop. This is better than the productivity rate of 5 labor days per rule used in the previous study. We will assume the more conservative 5 days per rule rate.

4. Assume a labor rate of $400.00 per man-day for expert systems software development (this is nearly double the rate assumed for the last study).

5. Assume $1M for verification of each element for a total of $7M.

6. Based on the estimate of one general processor for each on-line function plus one for the expert system selector, we can estimate that at least three onboard general processors would be needed to implement the system. Assuming $1M for each we have $3M for additional hardware.

Assembling the results of all the assumptions above gives a cost figure for the expert systems development and implementation of $24.2M.

For the benefits estimate we will consider a phased introduction of the integrating controller expert systems. This means that the yearly savings assumed in the previous study would be reduced.

The following assumptions apply to the benefits estimates for this study.

1. The labor to monitor the space station systems would be phased out as the integrating controller is phased in as follows.
   a. For year 1: Six ground-based mission controllers plus ½ time astronaut (full coverage)
   b. For Year 2 thru year 5: One ground-based mission controller plus ½ time astronaut. (Reduction of five ground-base mission controllers for 4 years.)
   c. For year 6 thru year 10: 1/10 time ground-based mission controller plus 1/10 time astronaut. (Reduction of 5.9 mission controllers and 0.4 astronaut for 5 years.)

2. Mission controller labor rate is $1500 per 24-hour day or $550,000 per year for each controller.

3. Astronaut labor rate is $77,000 per 24-hour day or $28,200,000 per year.

4. Resupply and maintenance cost savings due to the integrating controller are estimated as $25M over a 10-year mission due to more efficent use of resources onboard and more managed maintenance operations.

5. Half of the above benefits of an integrating controller can be attributed to use of expert systems.

Based on the above assumption the benefits of the expert systems part of an integrating controller are estimated at $54M.

The resulting cost to benefits ratio then is 0.44. This is a significant movement from the 0.098 ratio estimate of the previous report but still leaves the expert system development with all the associated unquantified benefits as an attractive tecnhology for advancement.

5.3.9 Identification of Technologies for Advancement

The technology indicated for advancement is to support the development of an integrating controller for a space station using expert systems for the mechanization of controller functions.

The following tasks are identified to describe the needed advancement in order to provide for an integrating controller on the space station.

1. Define expert system decisions.
   Review the functions of the integrating controller and identify where non deterministic deicisions have to be made. These would be decisions that either depend on more data than is available or on processes that have not been previously codified. In some cases expert systems decisions will be those in which no clear process is available and the best, to our expert, process will be used.

2. Acquire initial knowledge base.
   Identify and set up interview sessions with a set of experts to provide knowledge for, each of the decisions identified. These interview sessions would be conducted by knowledge engineers or specialists who would be trained in the use of natural language programming and who can interact with the expert to extract the knowledge. The initial experts will be chosen from candidates who are:
   a. Skylab or Shuttle Astronauts
   b. Mission Control Center Specialists
   c. System designers
   d. Technical specialists

For each decision process, one expert will be selected and used to develop the initial knowledge base.

As a part of developing the knowledge base the knowledge engineers will code expert systems rules and interact with the expert on the result.

3. Program the integrating controller functions.
   Using the expert systems decisions with the initial knowledge bases and the deterministic functions, each integrating controller function will be programmed. System modules will be identified that can be stored off line and called up by an expert system selector elements to implement the overall integrating controller. Initially, the system will be an interactive or advisory type. This means that the astronauts will be performing functions as data gathers or implementers of action according to interactive advise given by the system.

4. Exercise the integrating controller with future space station operation astronauts.
   Using the integrating controller programmed into an interactive system conduct exercises with future operations astronauts for the space station using a set of situations typical of expected space station anomalies. Using the results of this exercise return to the experts with any needs for updating or adjusting the expert systems, or the other parts of the integrating controller.

The following tasks are identified to implement the initial integrating controller.

1. Establish the baseline integrating controller for the initial space station.
   Using the updated integrating controller program establish flight software that is tailored to onboard flight hardware and to an operational architecture to be used on the space station.

2. Verify the integrating controller flight baseline.
   By using the system in a space station mockup with operations astronauts and a set of expected situations, check out the baseline integrating controller.

The following tasks are identified to describe the needed updating of the initial system to reach the desired configuration.

1. Update the baseline system.
   During the first several years of flight, the operations personnel for each crew would be interviewed by knowledge engineers as they return from their 90-day tours. These interviews will be used to update the knowledge base for the expert systems used on the space station.

2. Automated integrating controller functions.
   Based on astronaut experience functions to be automated (rather than being interactive) will be identified. This will be largely in response to astronauts preferences; some things they will want to hang onto others they will want to be rid of. For those where sensors or actuators are feasible integrating controller functions will be reprogrammed to rid the astronauts of unwanted interactions. An ongoing program to identify where sensors/actuators are likely to be wanted and to initiate necessary developments should be defined early in the effort.

5.4 SUMMARY OF RESULTS

This section summarizes the results of the tasks conducted on the Integration of Automated Housekeeping for an inhabited space station as part of this study.

5.4.1 Task 1 Results

The first major result is the identification of automation functions and quantities to be sensed to perform those functions. Tables 5.3-1, 5.3-2, and 5.3-3 list these for the electrical power subsystem, the life support subsystem and the thermal control subsystem respectively. These functions and sensor indicators were used to identify the major result of task 1. This result is the description of six functions to be performed by an integrating controller. These six functions are described and diagrammed under section 5.3.3 and are listed here as follows:

1. Electrical power load management.
2. Materials transfer management.
3. Intersubsystem failure isolation.
4. Intersubsystem redundant path selection.
5. Maintenance schedule management.
6. Start-up integration.

Another result is that the processing for the integrating controller will be partly functionally distributed and partly functionally centralized on board the space station. The exact organization of hardware remains undetermined at this time because the configuration of the space station as well as groundrules for the architecture of the data processing system are undefined. Figures 5.3-10 and 5.3-12 give indicators of how the system architecture and integrating controller hierarchy might be managed in a functional sense.

The final task 1 result was a review of expert system applicability to the integrating controller that indicates the following:

1. The integrating controller functions would profit from use of expert systems.

2. That the expert systems would require a large onboard data processing capability.

3. That selection of on-line expert systems elements from a mass memory storage device by an expert systems selector would be necessary.

4. That expert systems development costs would be significant because this integrating controller application exceeds anything that has been done to date in expert systems technology both in size and in the breadth of the functions covered.

5.4.2 Task 2 Results

The comparison of integrating controller functions indicated that the maintenance scheduling and start-up integration function were of lower priority than the other four.

Ground-based control and interactive onboard control have advantages in an early space station program with more autonomy both to the space station and to the automatic systems on board as the space station matures.

The cost of developing expert system elements for an integrating controller was reassessed based on the characterization developed in this study. The result was an increase in the estimated cost from $9.0M to $24.2M. Part of this was a more realistic labor rate figure for knowledge engineers and LISP programmers and part was the inclusion of implementation and post-launch updating costs.

The benefits from the expert system elements were also reassessed based on the phased implementation of the integrating controller now seen as a more likely possibility. This produced a $54.3M benefit as opposed to the $92M benefit estimated in the last study for the first ten years of the space station program.

The resulting 0.44 cost benefit figure for expert systems advancement is not as enticing as the 0.098 figure produced in the last study, but the greater figure from this study still indicates a worth while technology for advancement.

5.5 CONCLUSIONS

The conclusion from this study are:

1. The integrating controller has real and useful functions on a space station.

2. The implementation of the controller would profit from expert systems programming.

3. The implementation will be phased and updated during the early years of the space station operations.

4. The costs are high but so are the benefits.

5. This technology advancement is essential if the space station autonomy/automation philosophy listed on table 5.1-1 is to be implemented.

5.6 RECOMMENDATIONS

The recommendation from this study is to proceed with the technology development for expert systems elements and the implementation of an integrating controller as outlined in section 5.3.9.

Volume III of this report includes a section that defines a plan for development of this technology and implementation on a space station during the 1990's.